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(54) STRETCHABLE ELECTRONIC DEVICE AND METHOD OF MAKING THE SAME

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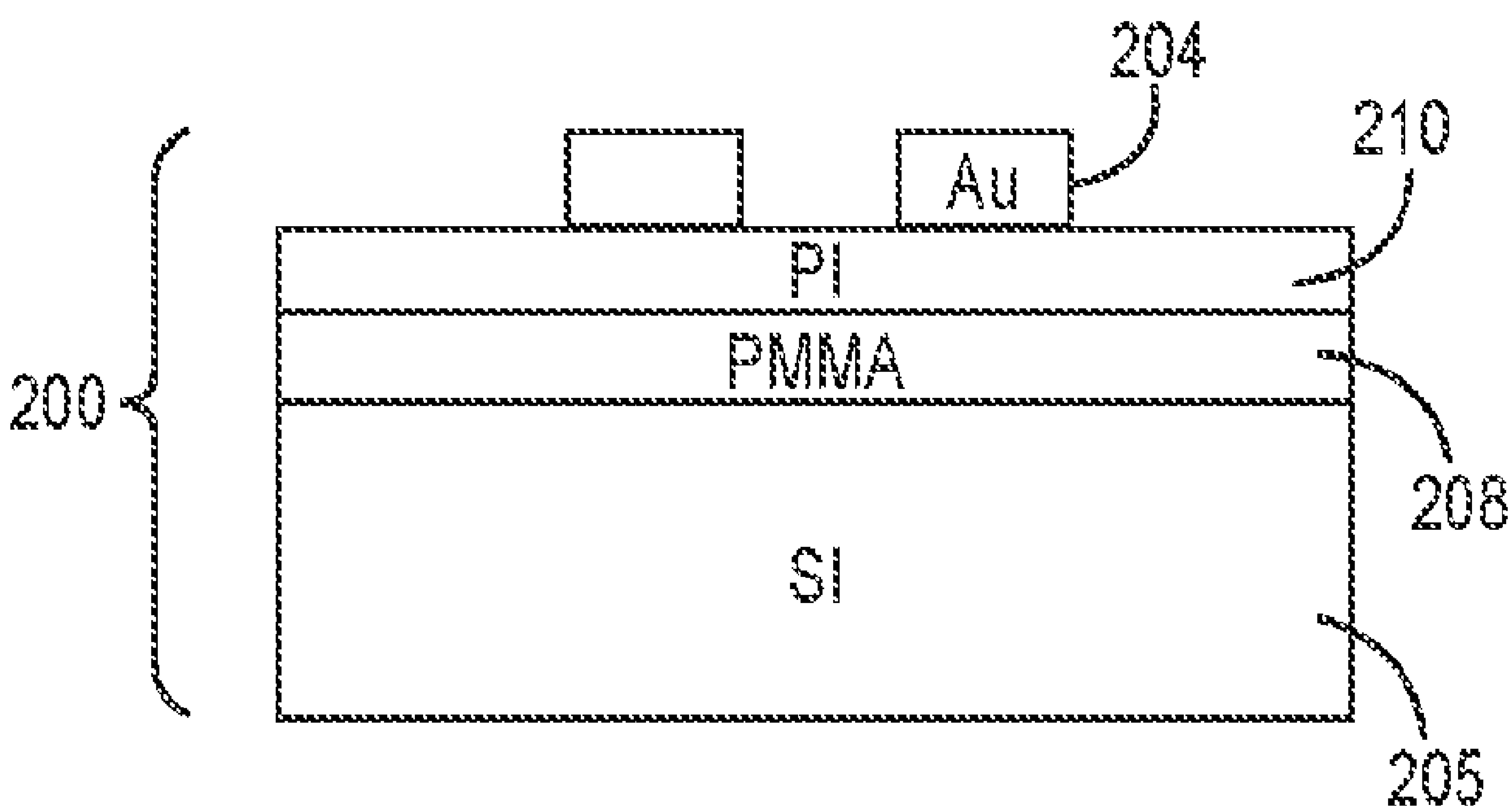
(52) **U.S. Cl.**

CPC ***H01L 33/62*** (2013.01); ***H01L 25/167*** (2013.01); ***H01L 33/005*** (2013.01); ***H01L 33/44*** (2013.01); *H01L 2933/0066* (2013.01); *H01L 2933/0025* (2013.01)

(57) **ABSTRACT**

A method of manufacturing a stretchable electronic device includes the steps of:

a) depositing a release layer on a temporary rigid substrate;
b) depositing a sacrificial layer on the release layer;
c) fabricating conductive traces and electrical contacts on top of the sacrificial layer;
d) mounting surface mount components (SMCs) to the electrical contacts;
e) depositing a first stretchable polymer layer over the conductive traces and SMCs to form a stretchable substrate;
f) separating the rigid substrate and release layer from the sacrificial layer and the stretchable substrate at an interface between the release layer and the sacrificial layer;
g) removing the sacrificial layer from the stretchable substrate; and
h) depositing a second stretchable polymer layer on a surface of the stretchable substrate exposed by removing the sacrificial layer.



Side View 3D View

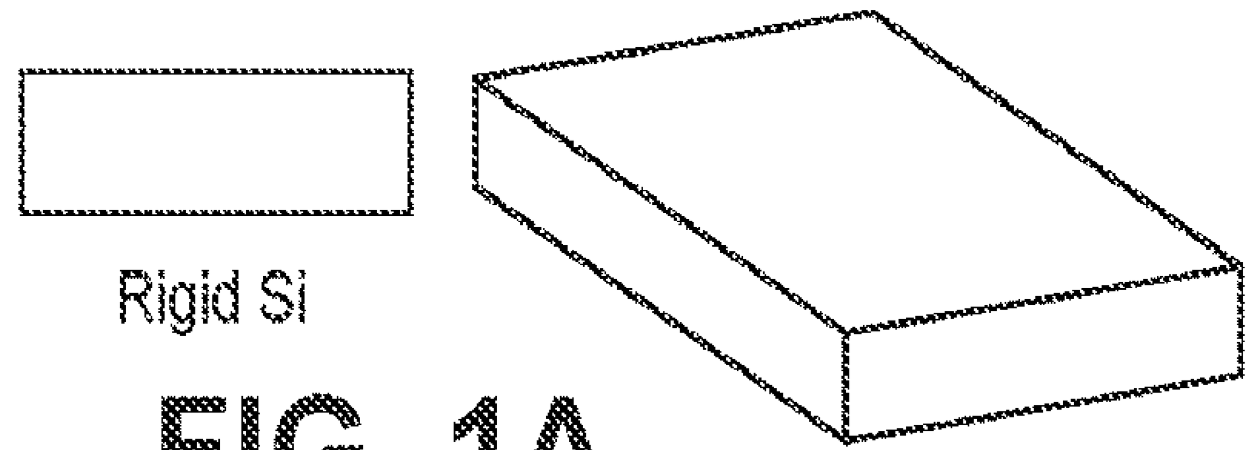


FIG. 1A

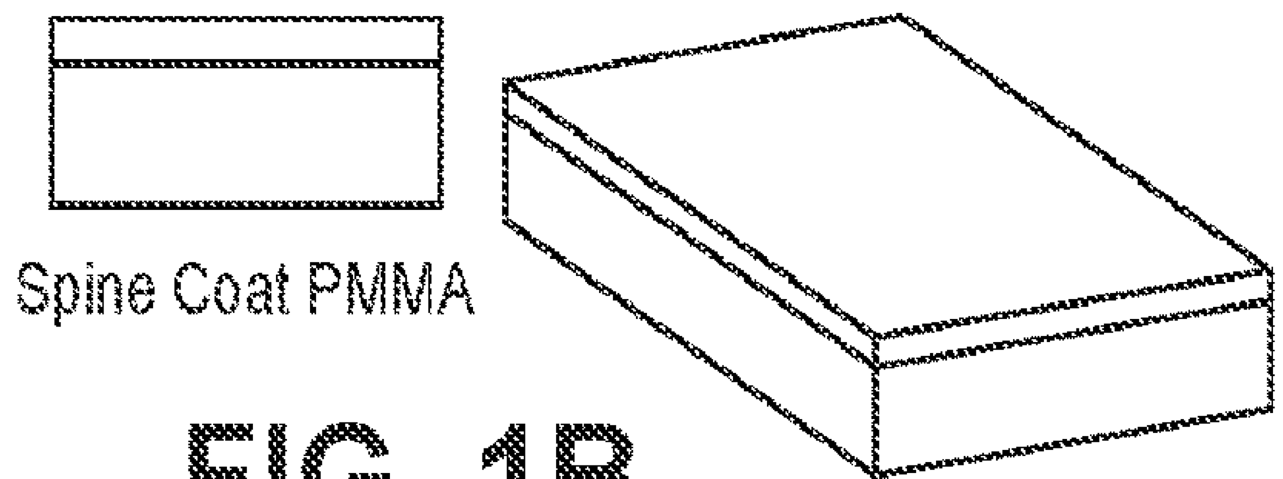


FIG. 1B

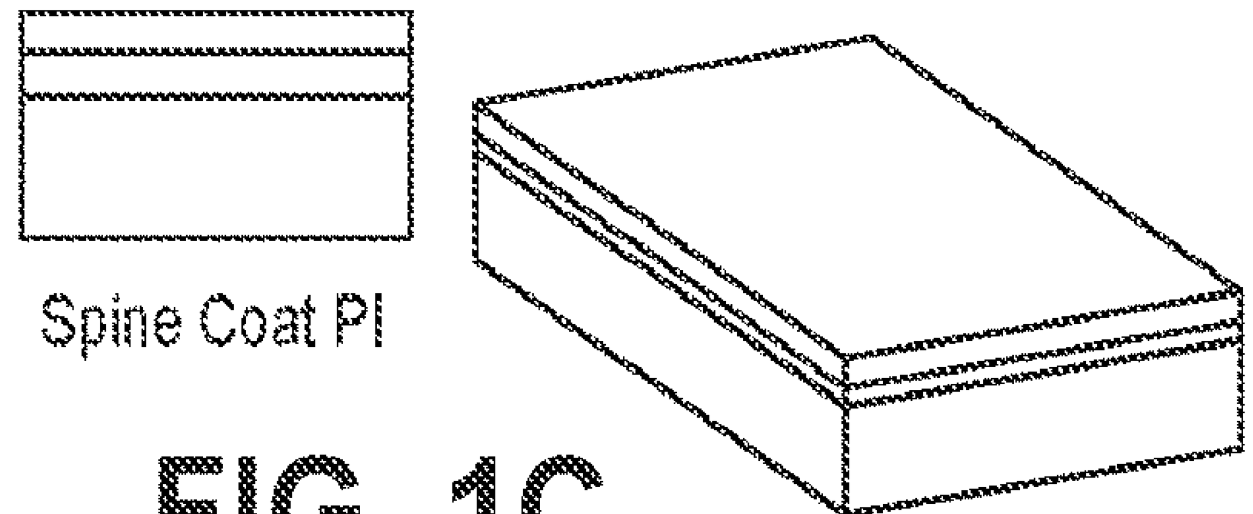


FIG. 1C

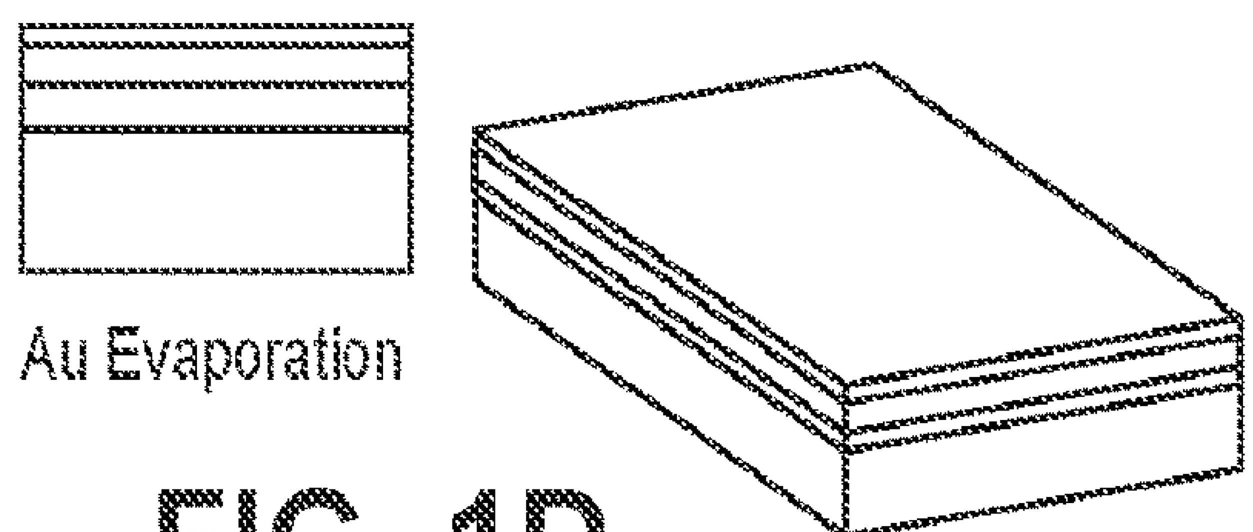


FIG. 1D

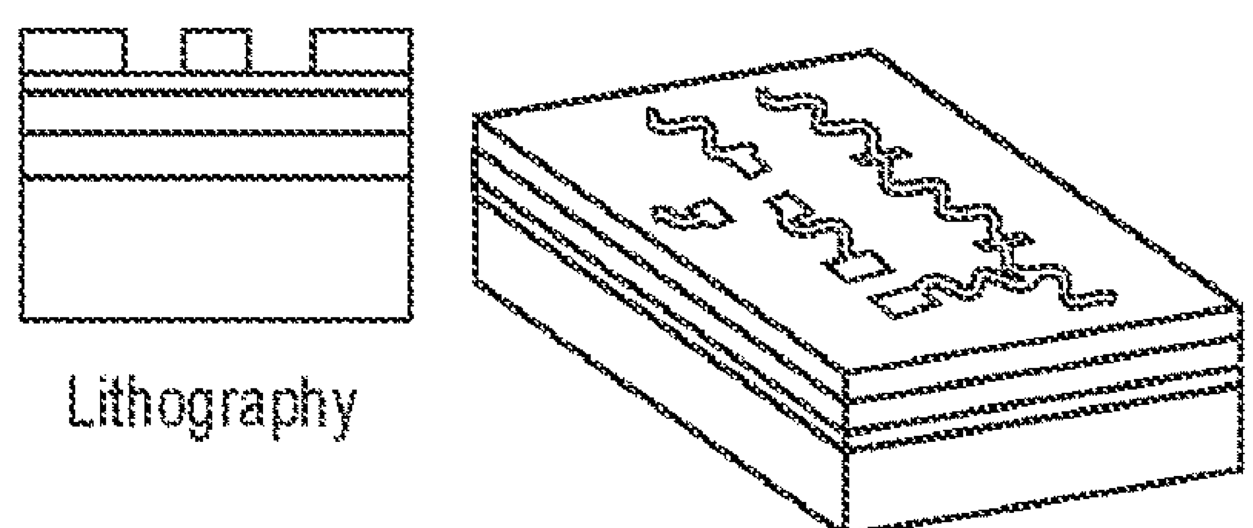


FIG. 1E

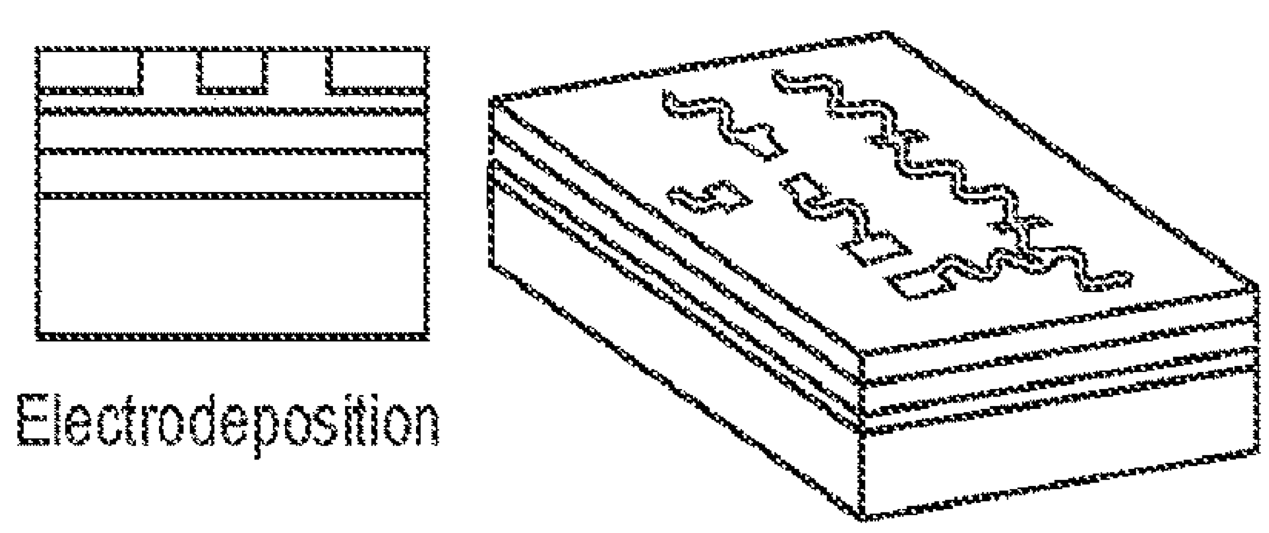


FIG. 1F

Side View 3D View

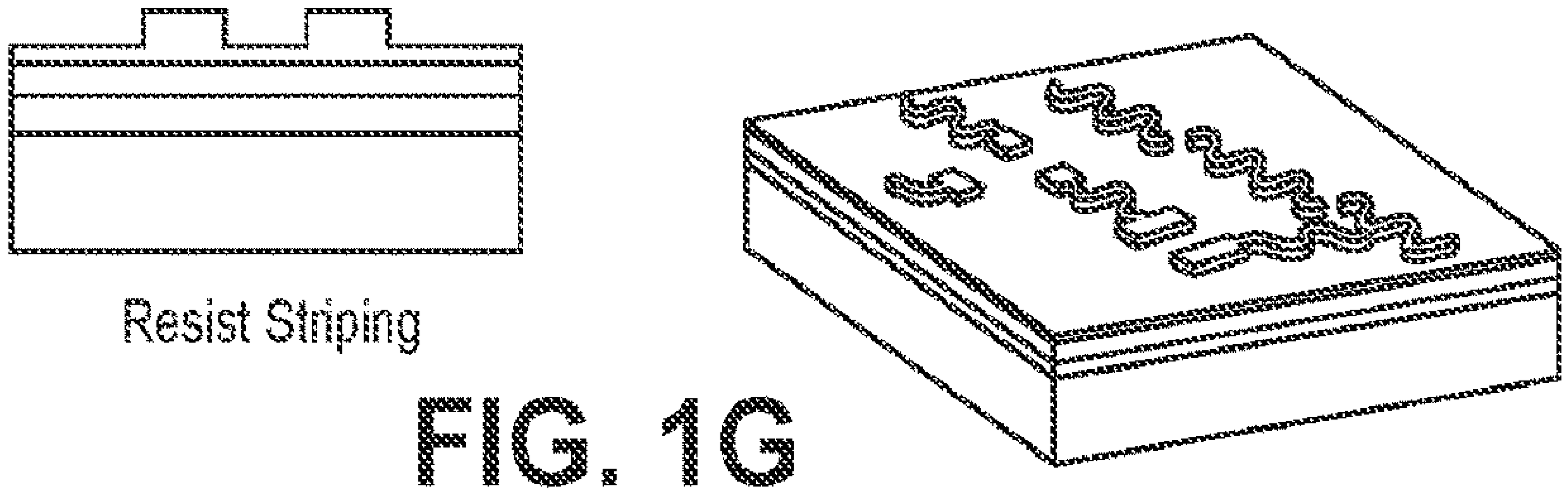


FIG. 1G

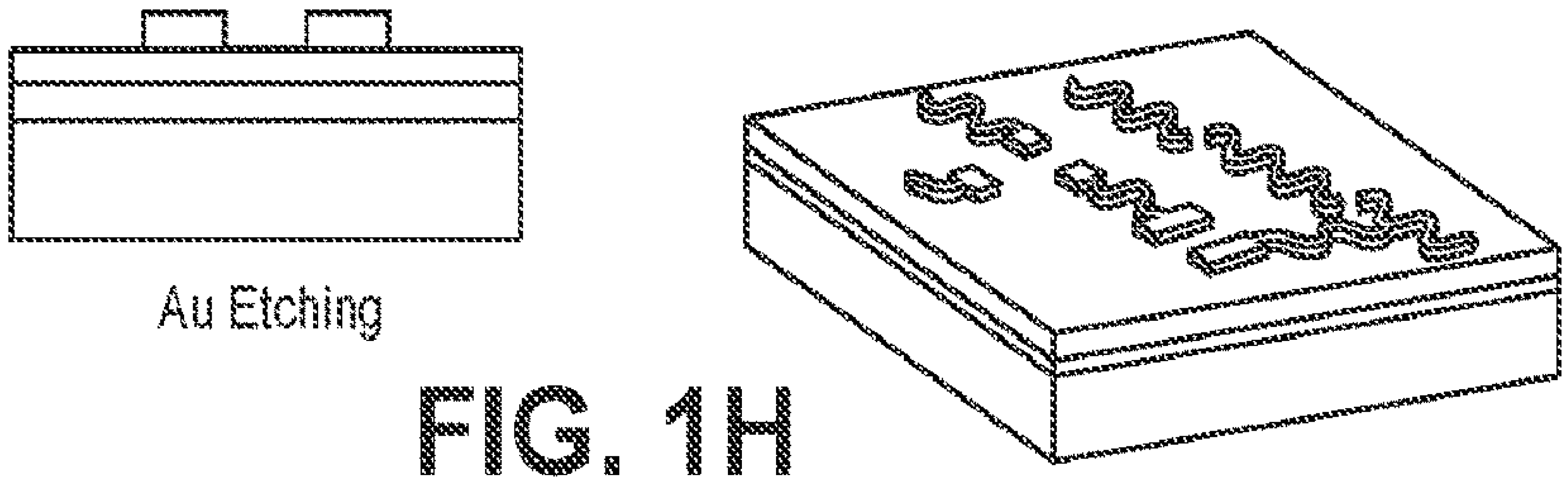


FIG. 1H

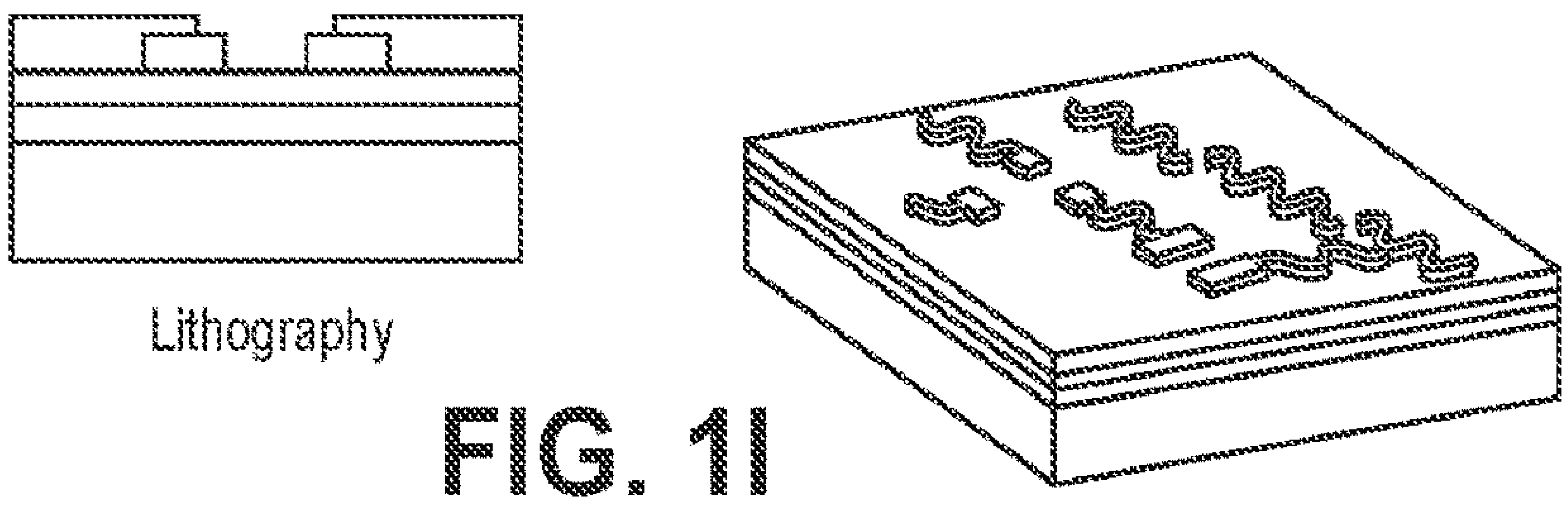


FIG. 1I

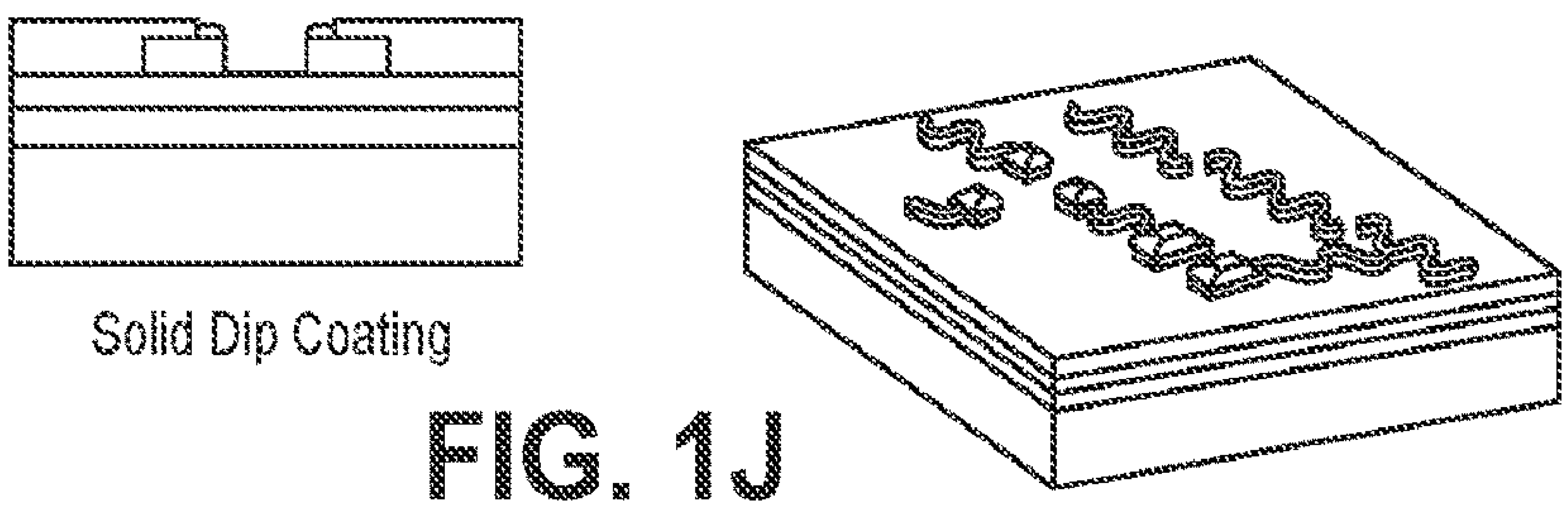


FIG. 1J

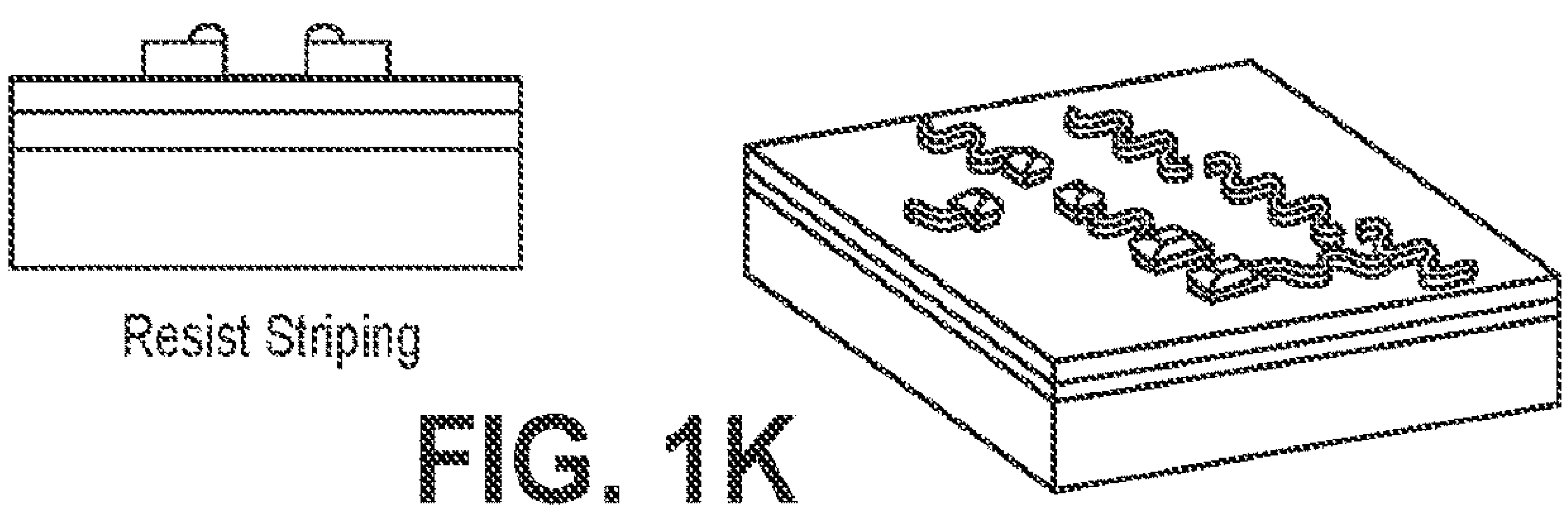


FIG. 1K

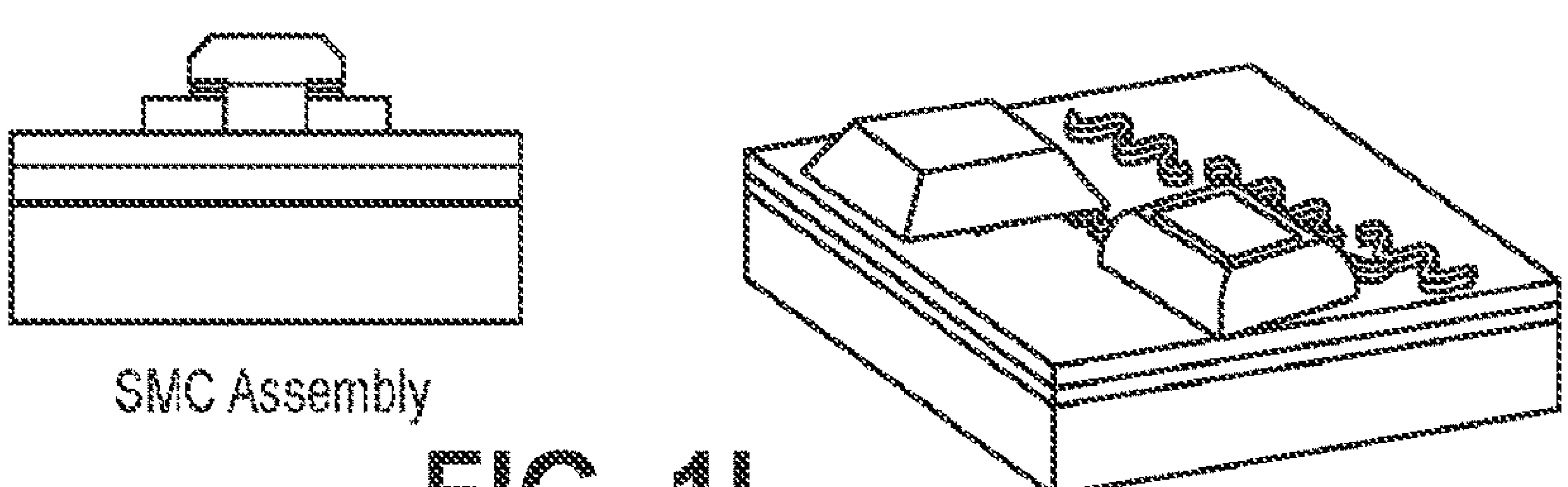


FIG. 1L

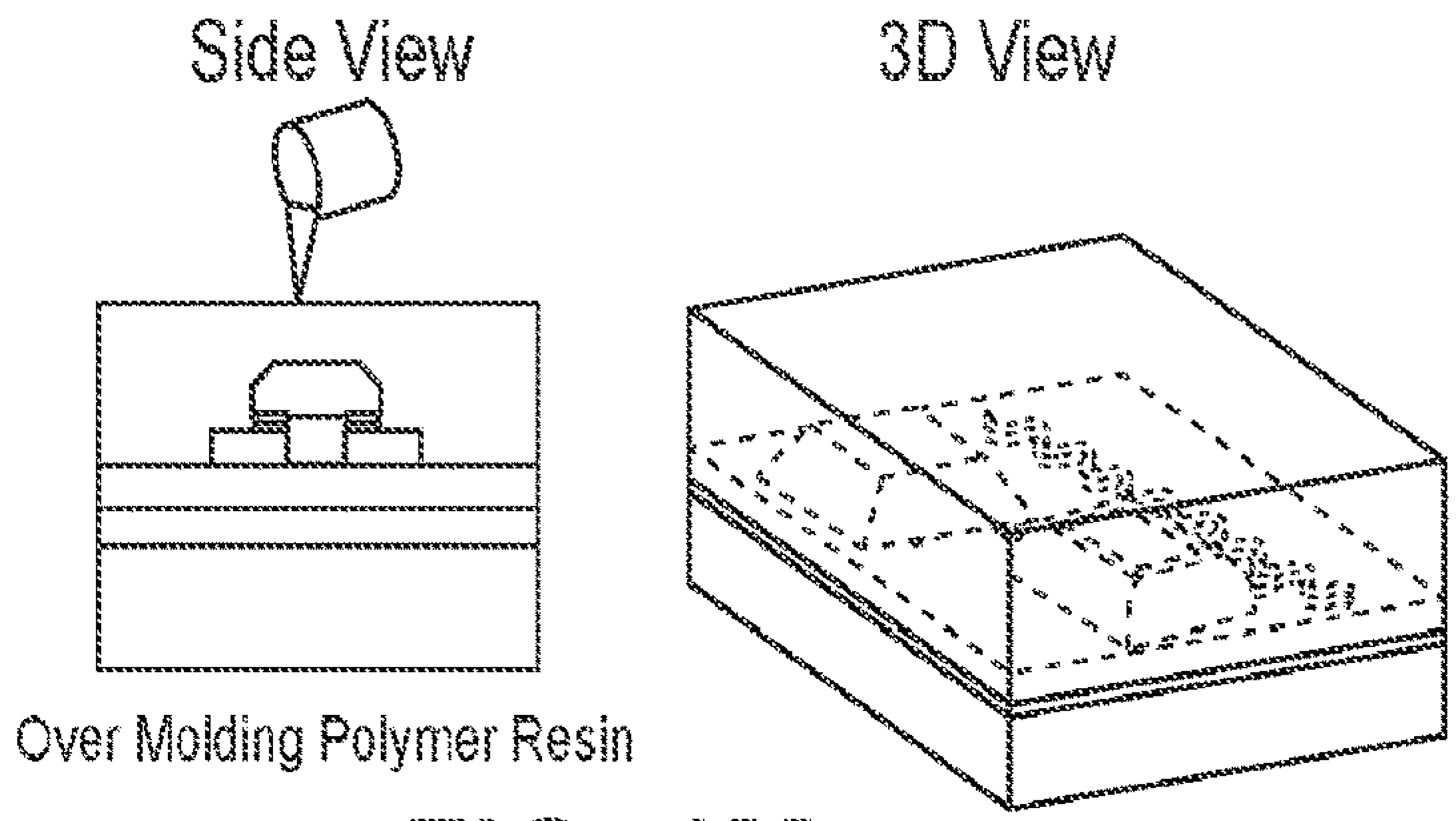


FIG. 1M

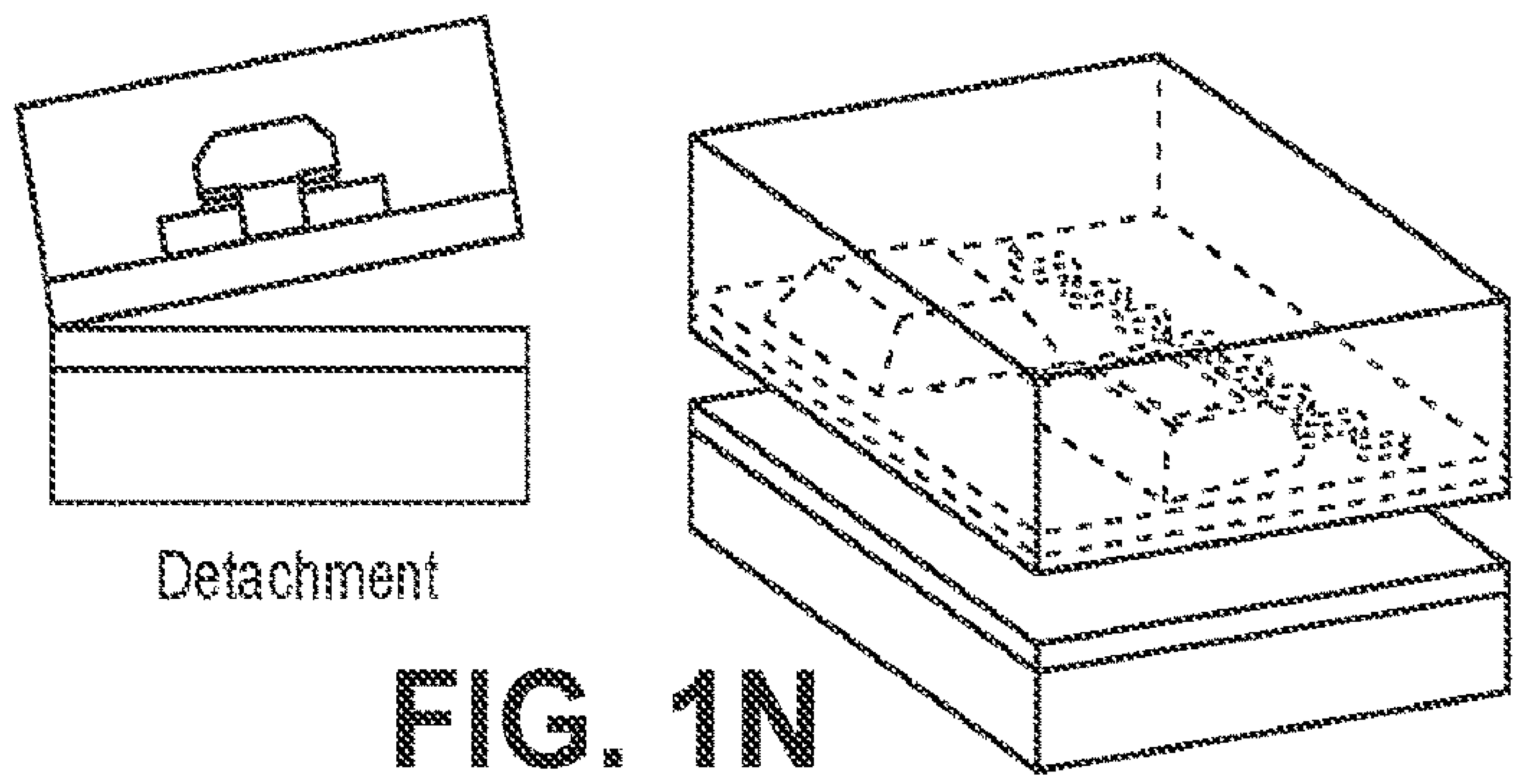


FIG. 1N

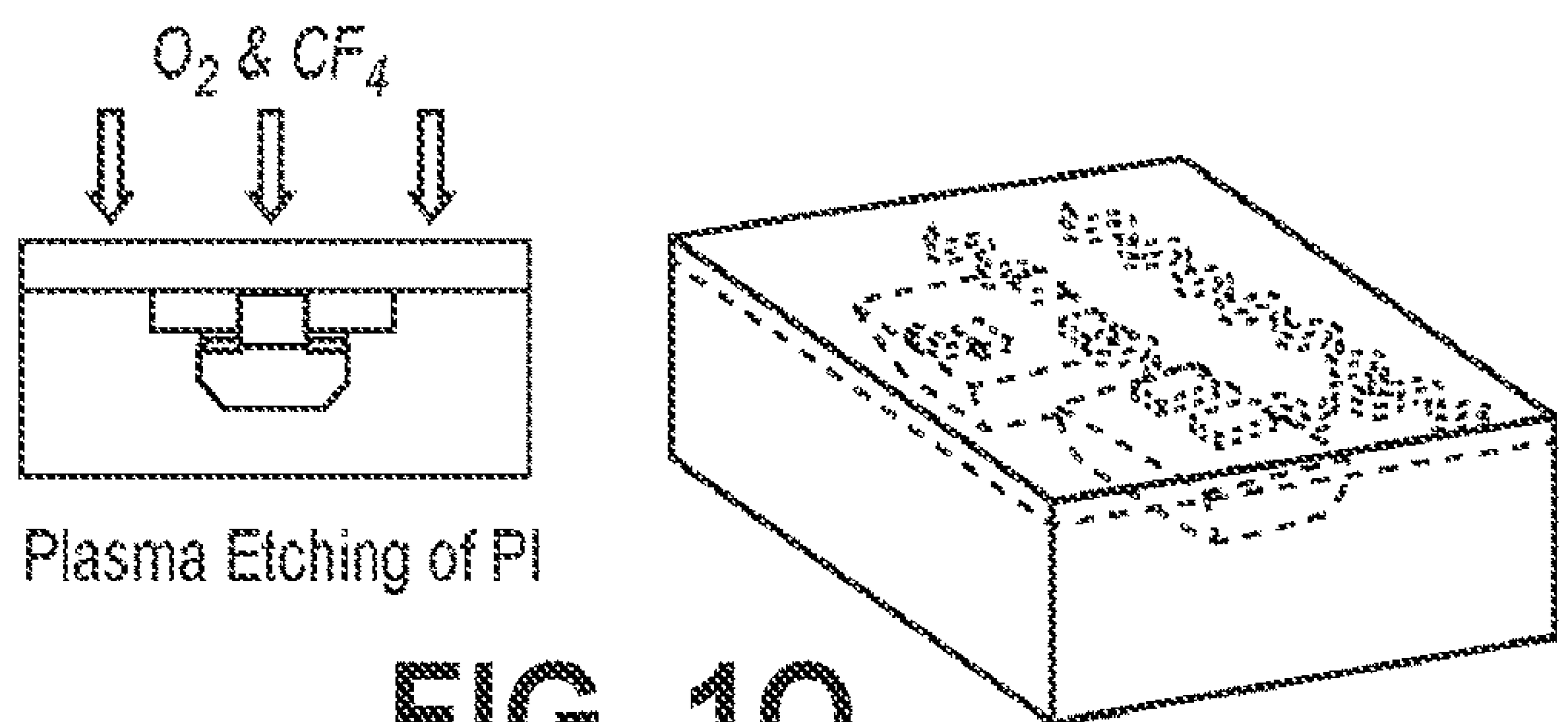


FIG. 1O

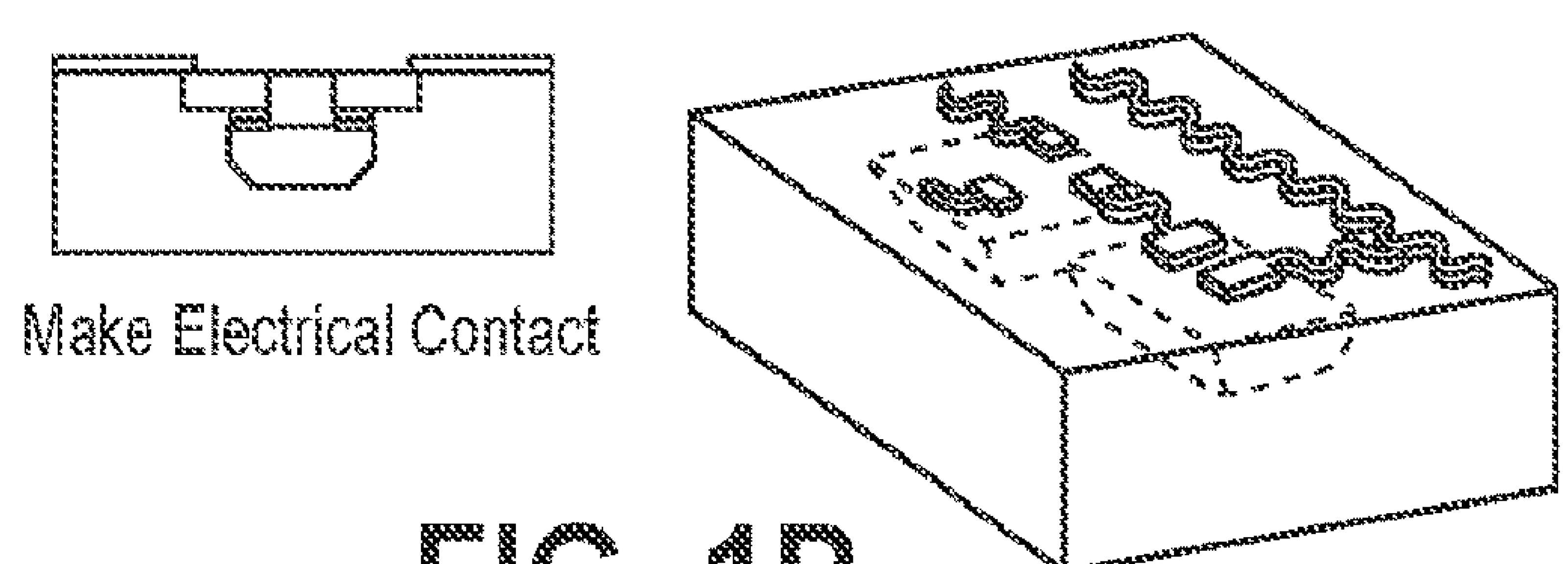


FIG. 1P

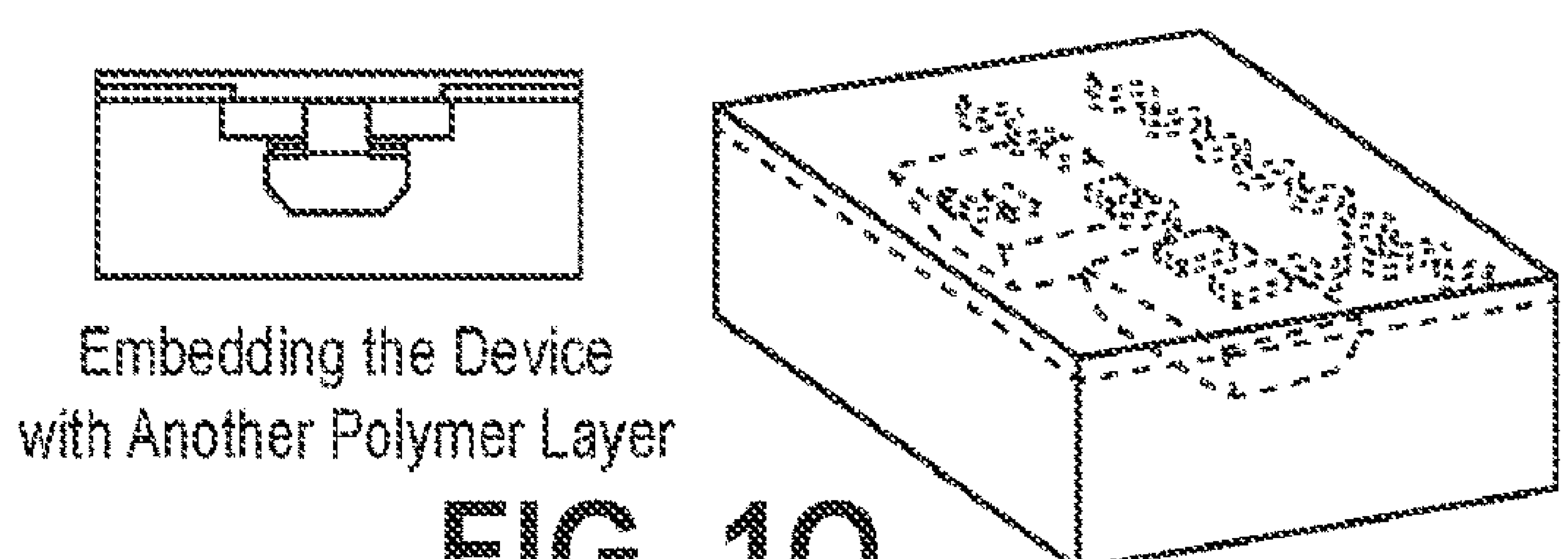


FIG. 1Q

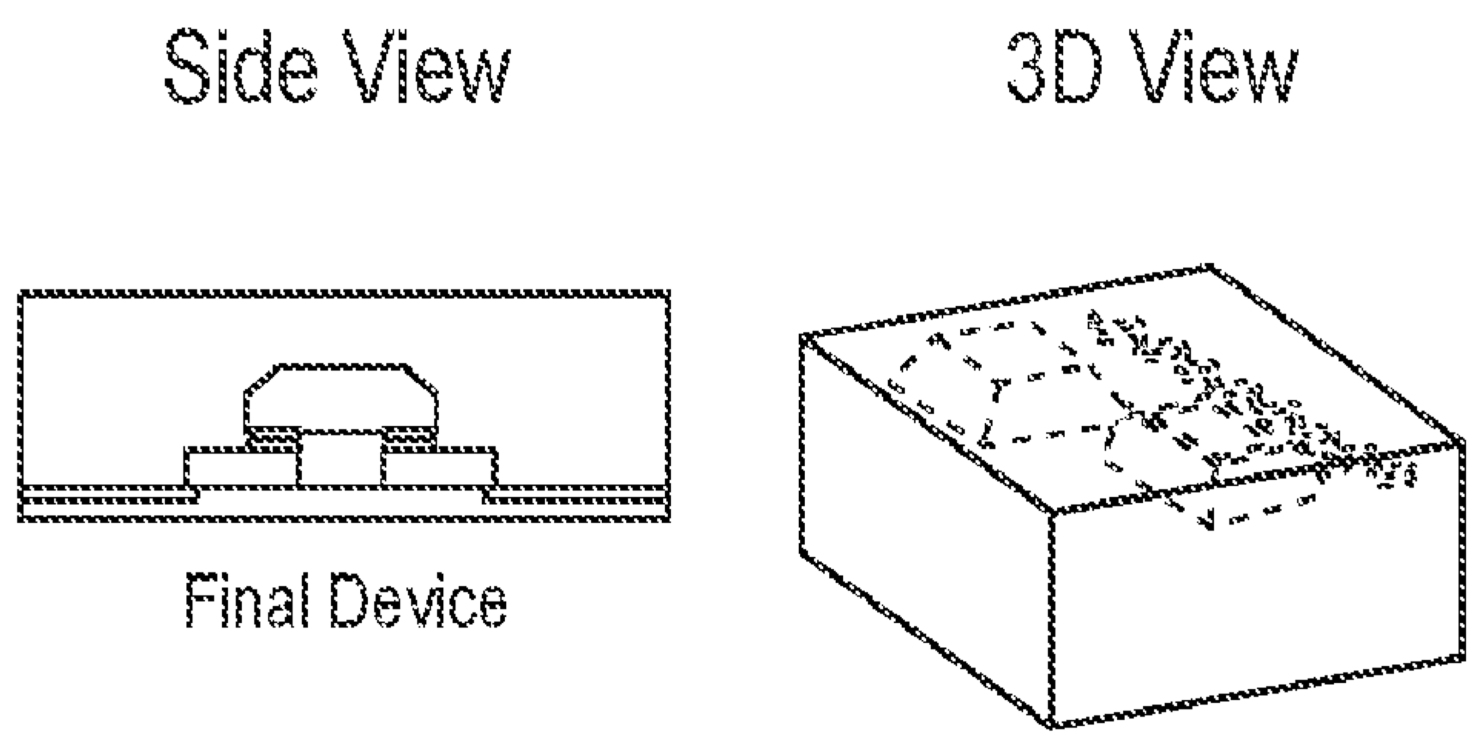


FIG. 1R

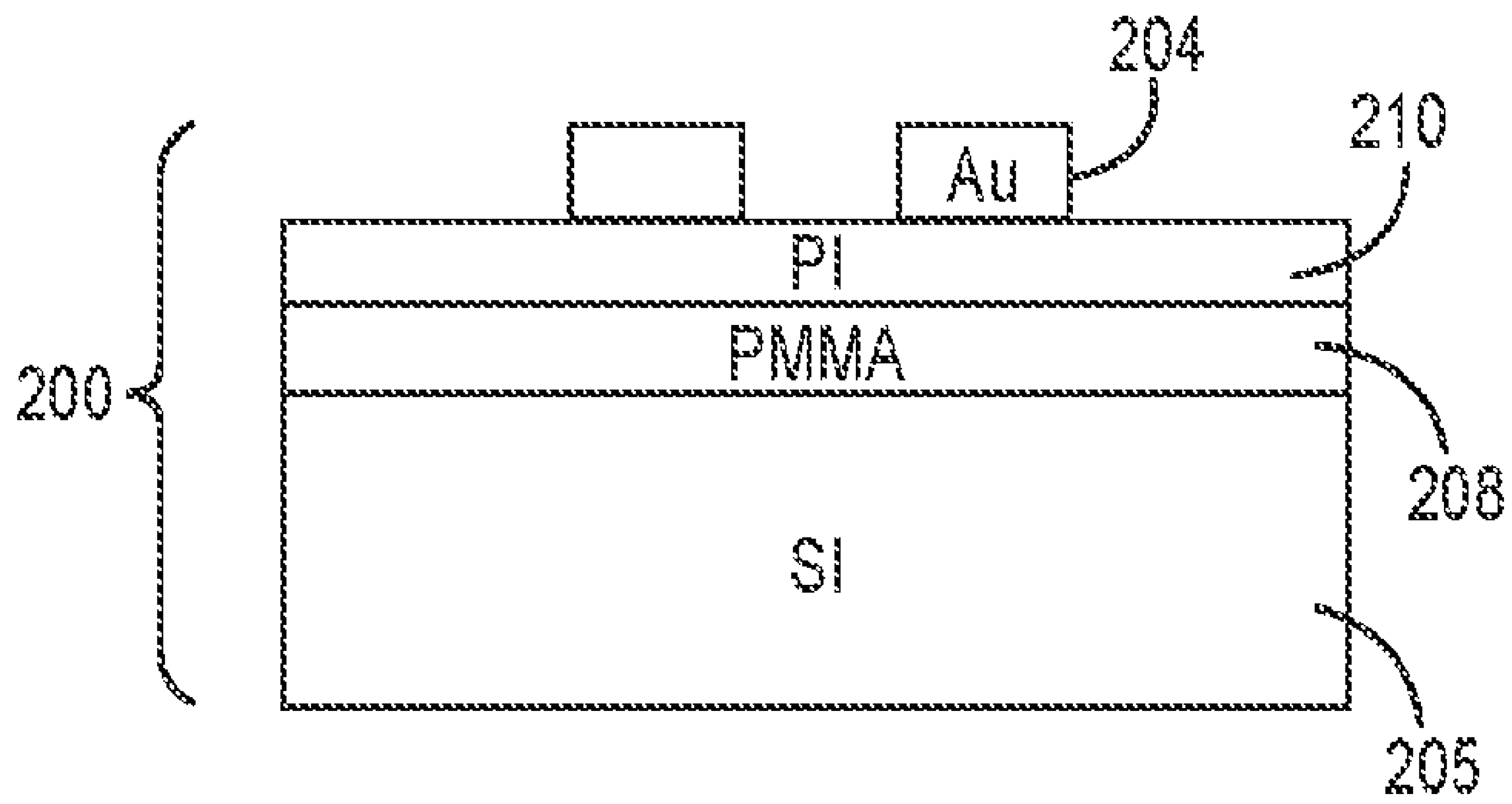


FIG. 2B

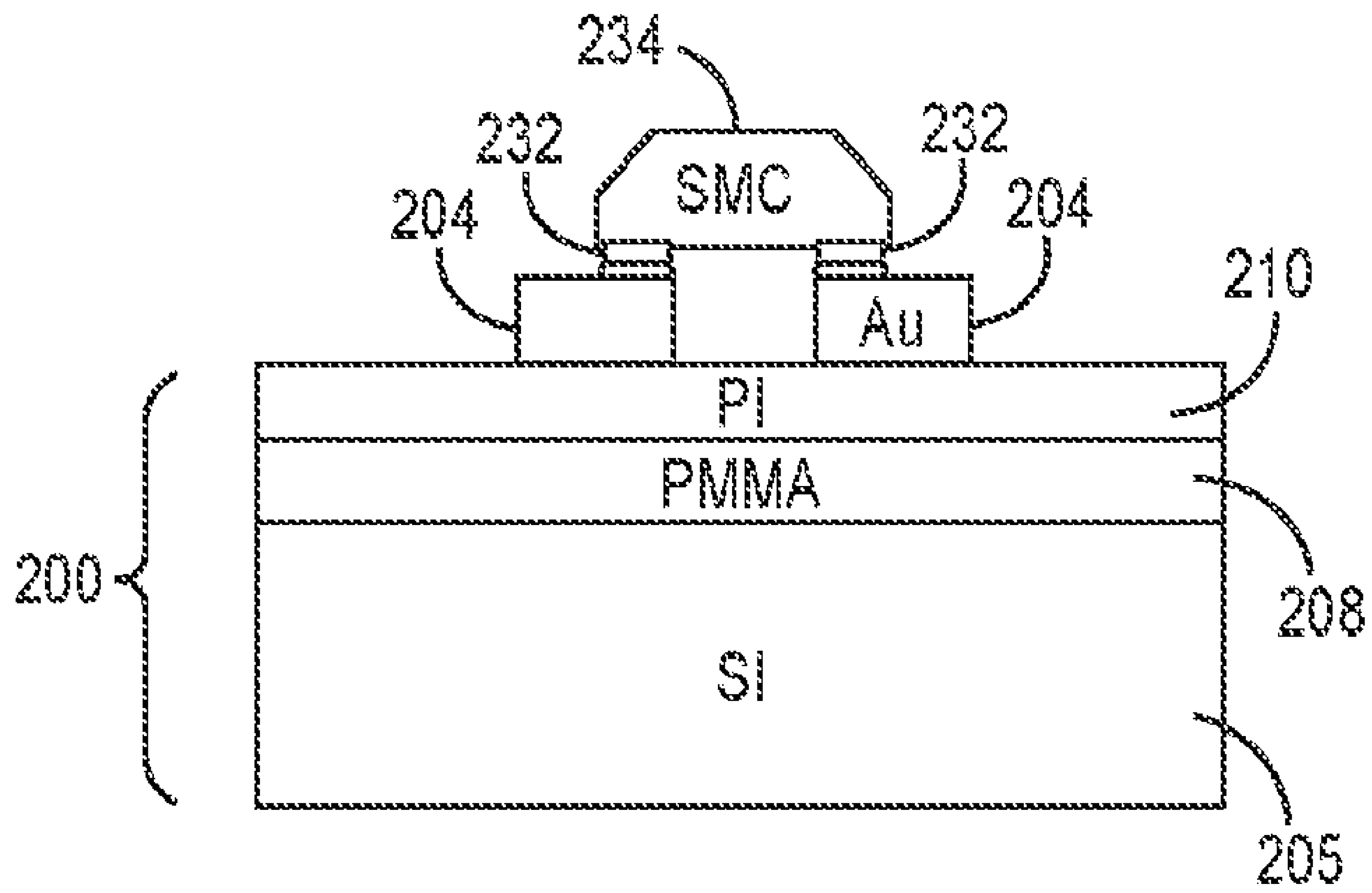


FIG. 2D

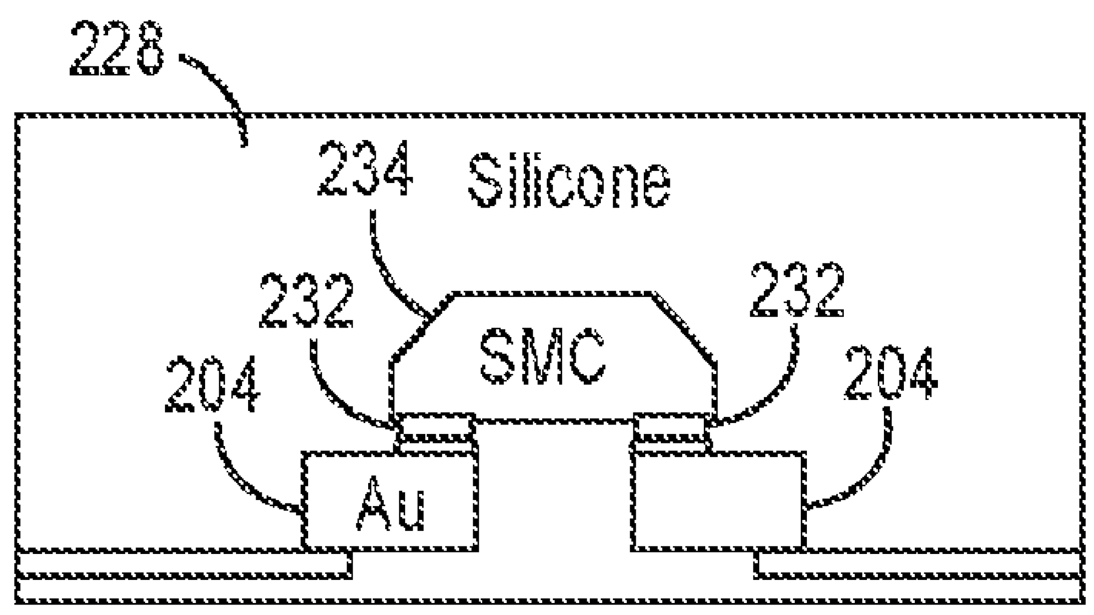


FIG. 2F

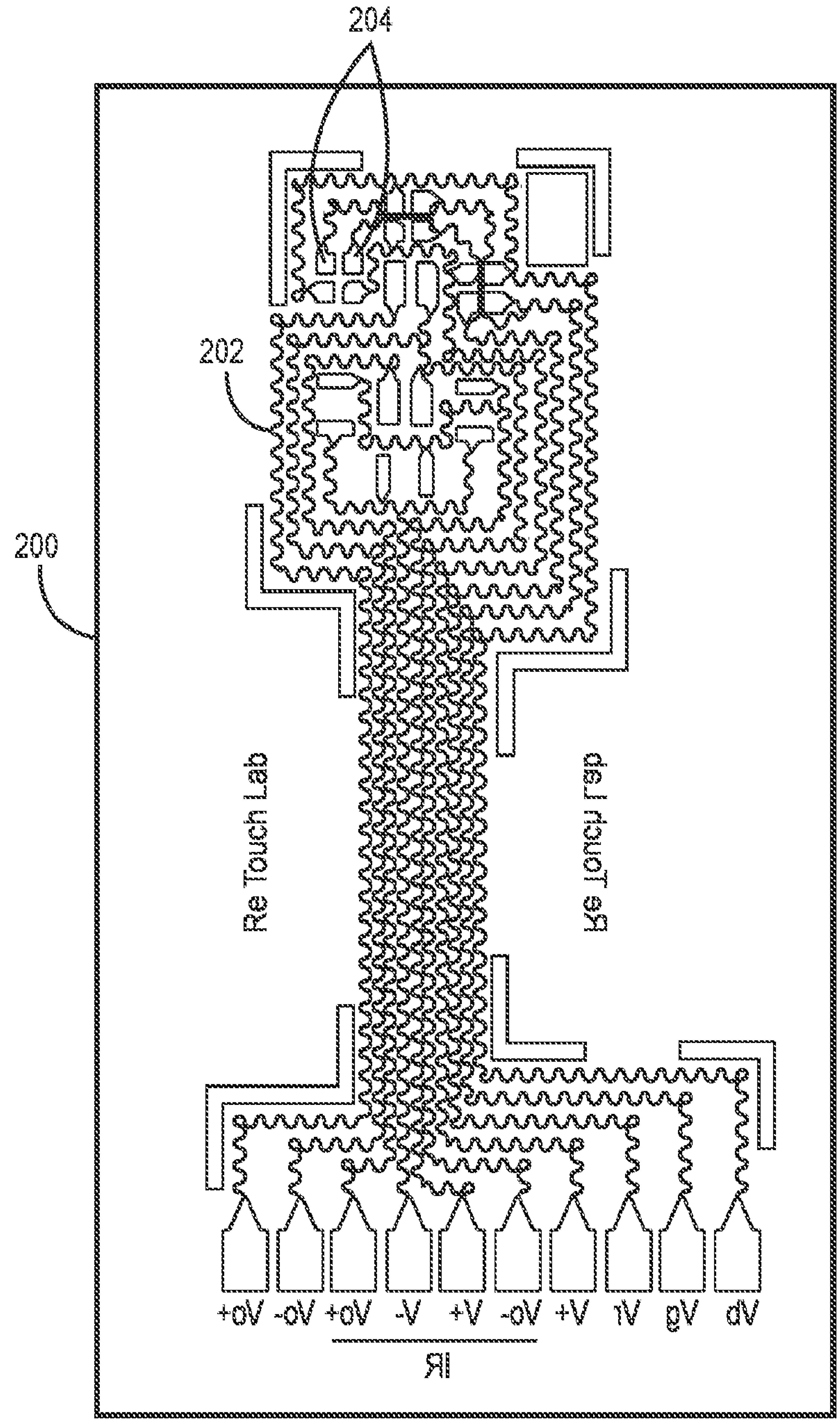


FIG. 2A

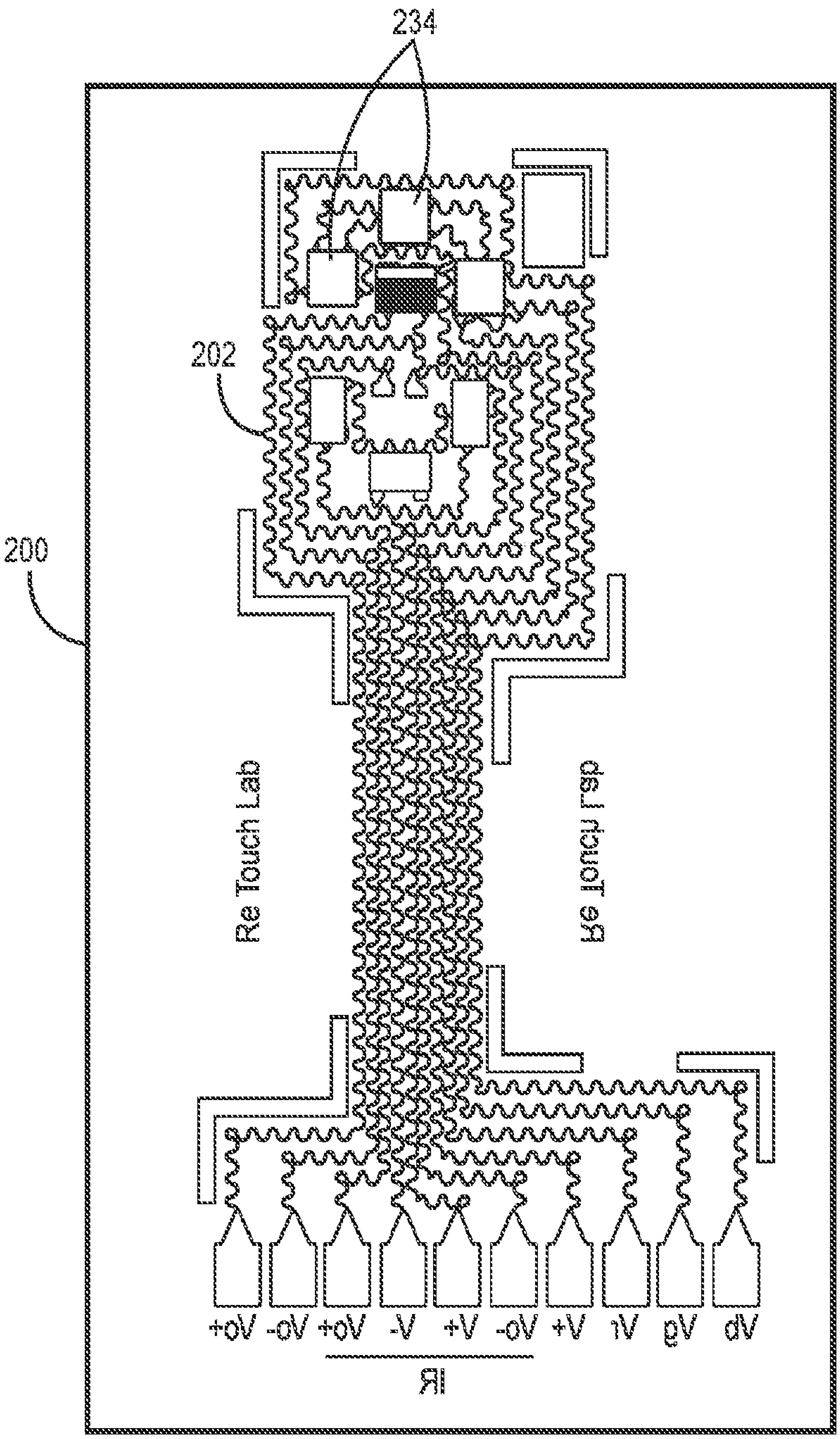


FIG. 2C

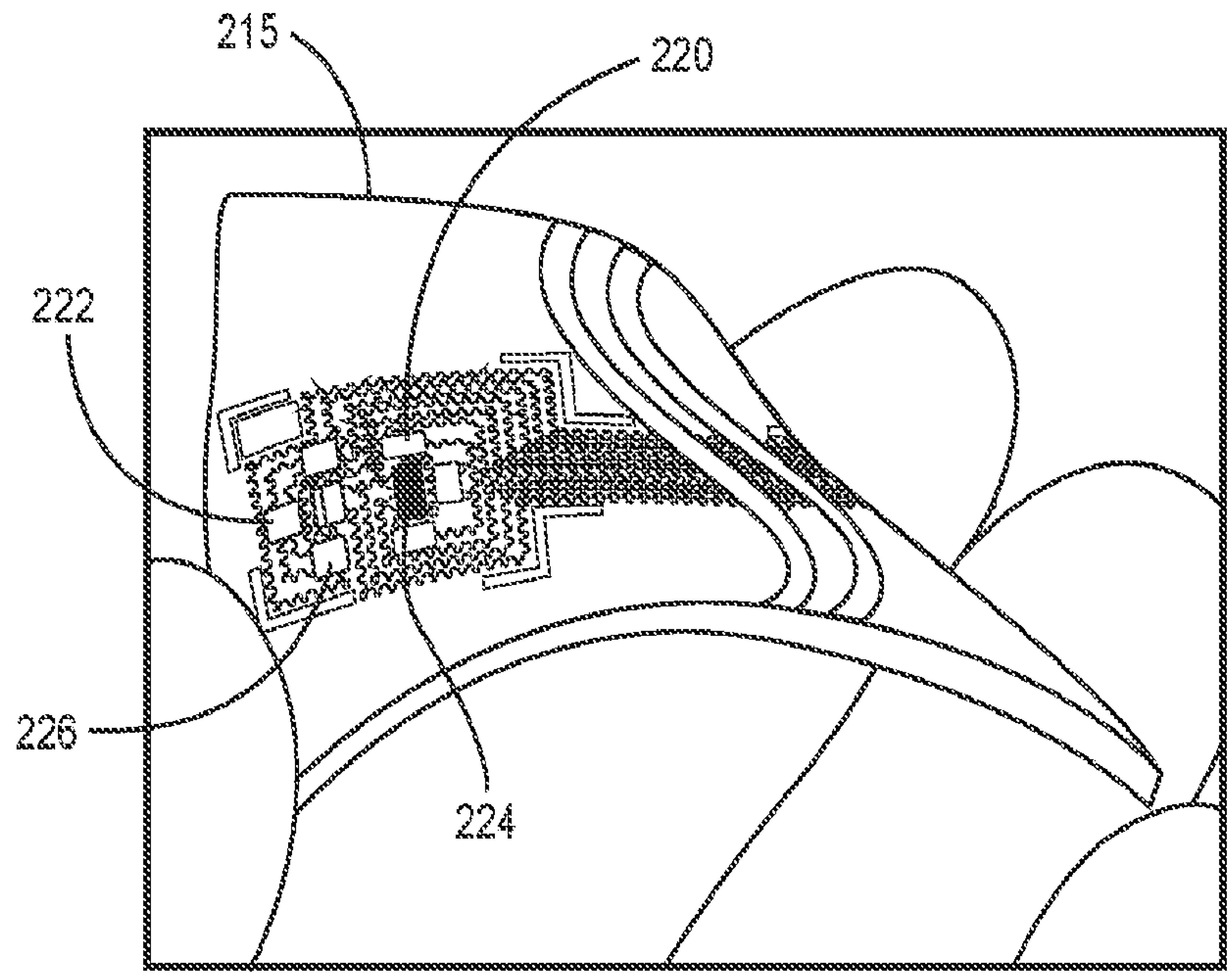


FIG. 2E

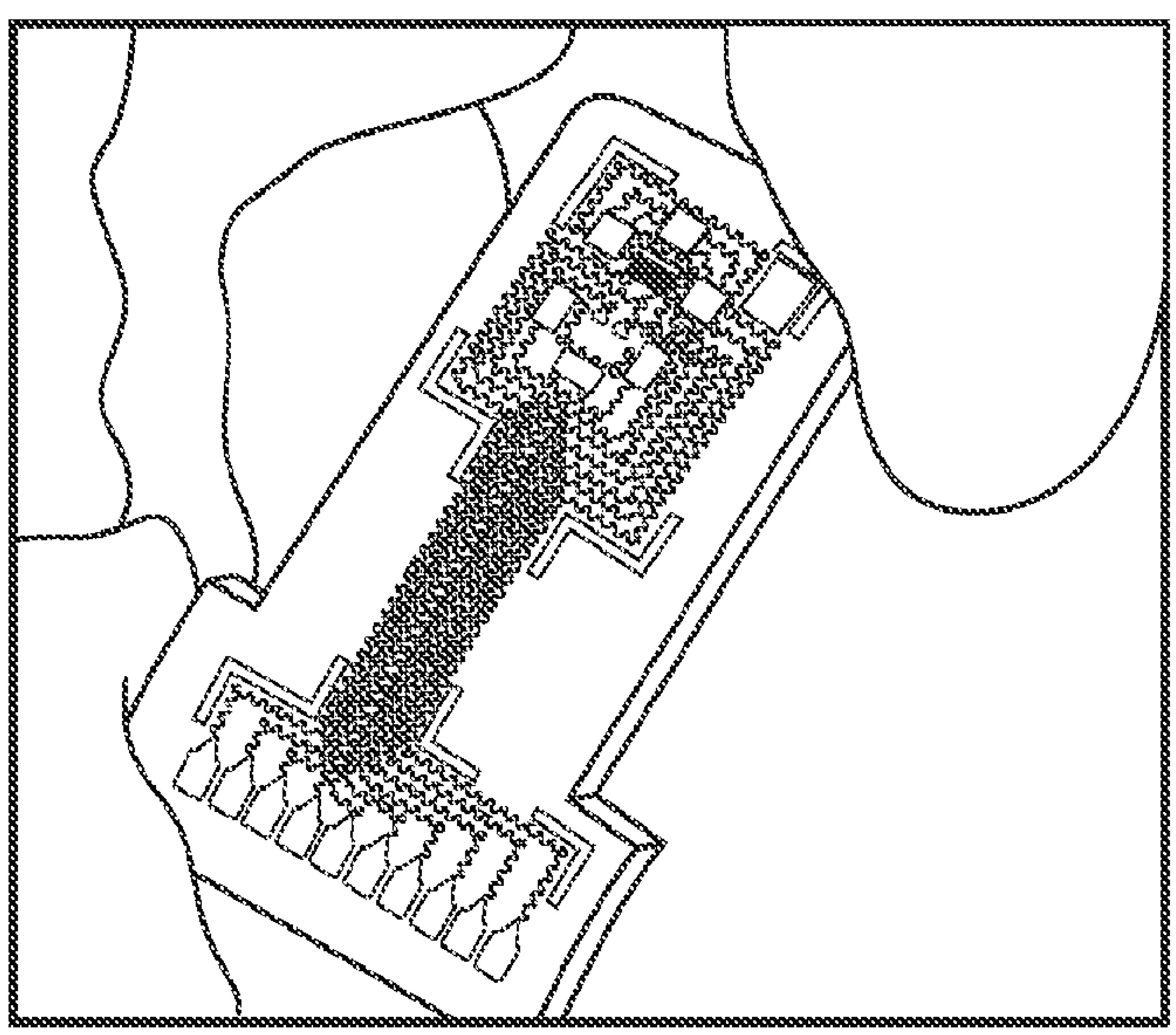


FIG. 2G

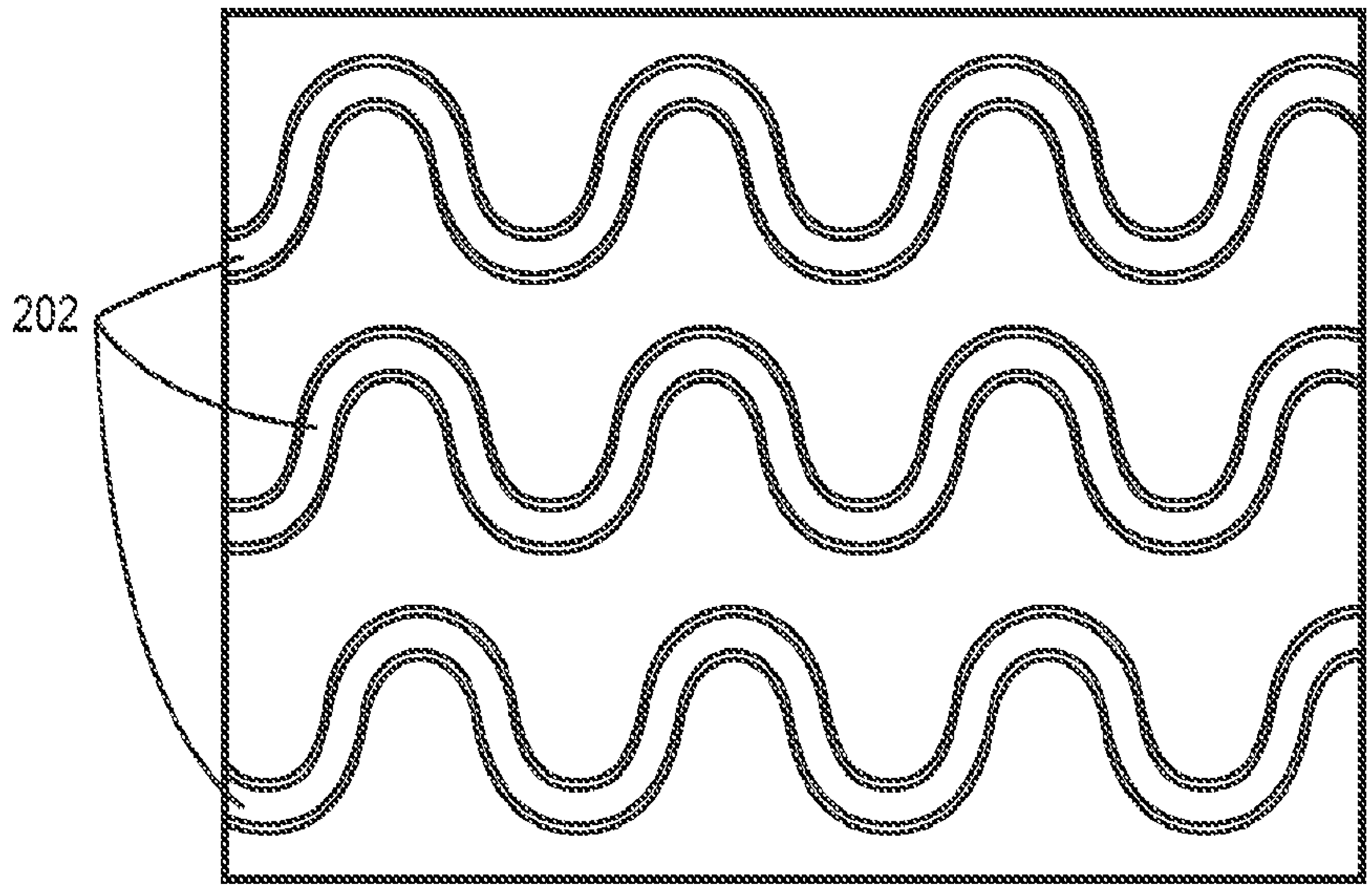


FIG. 2H

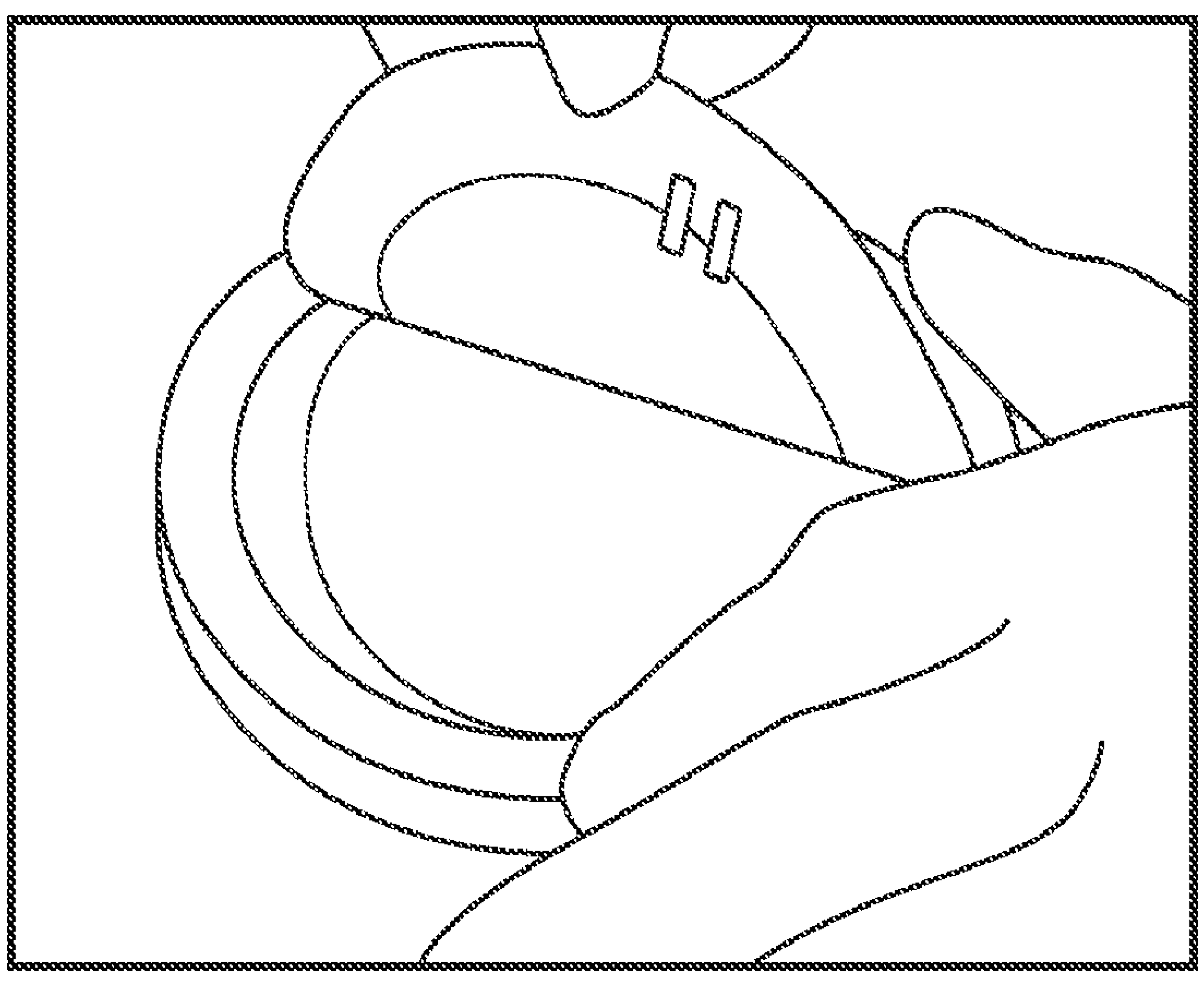


FIG. 3

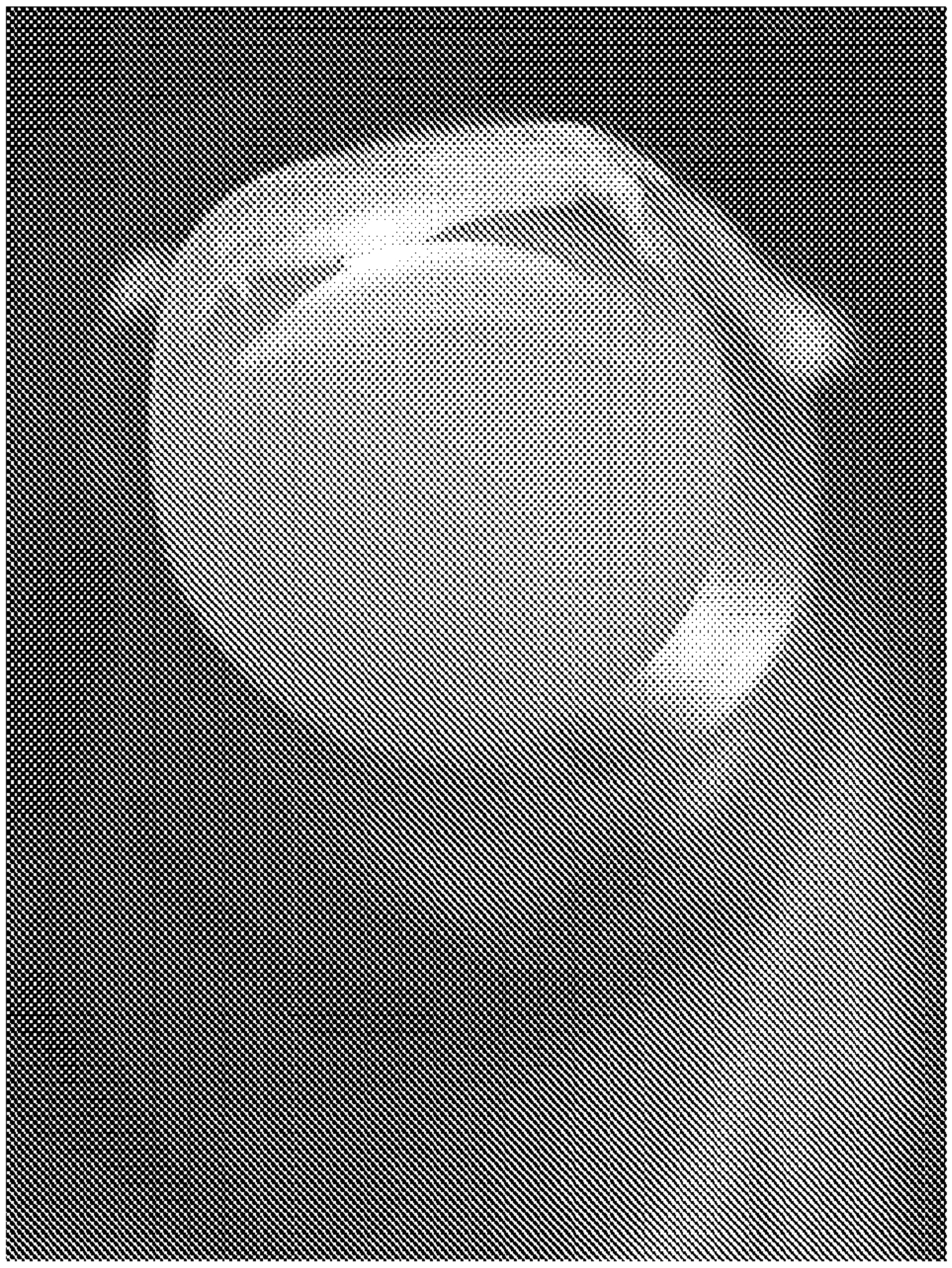


FIG. 4A

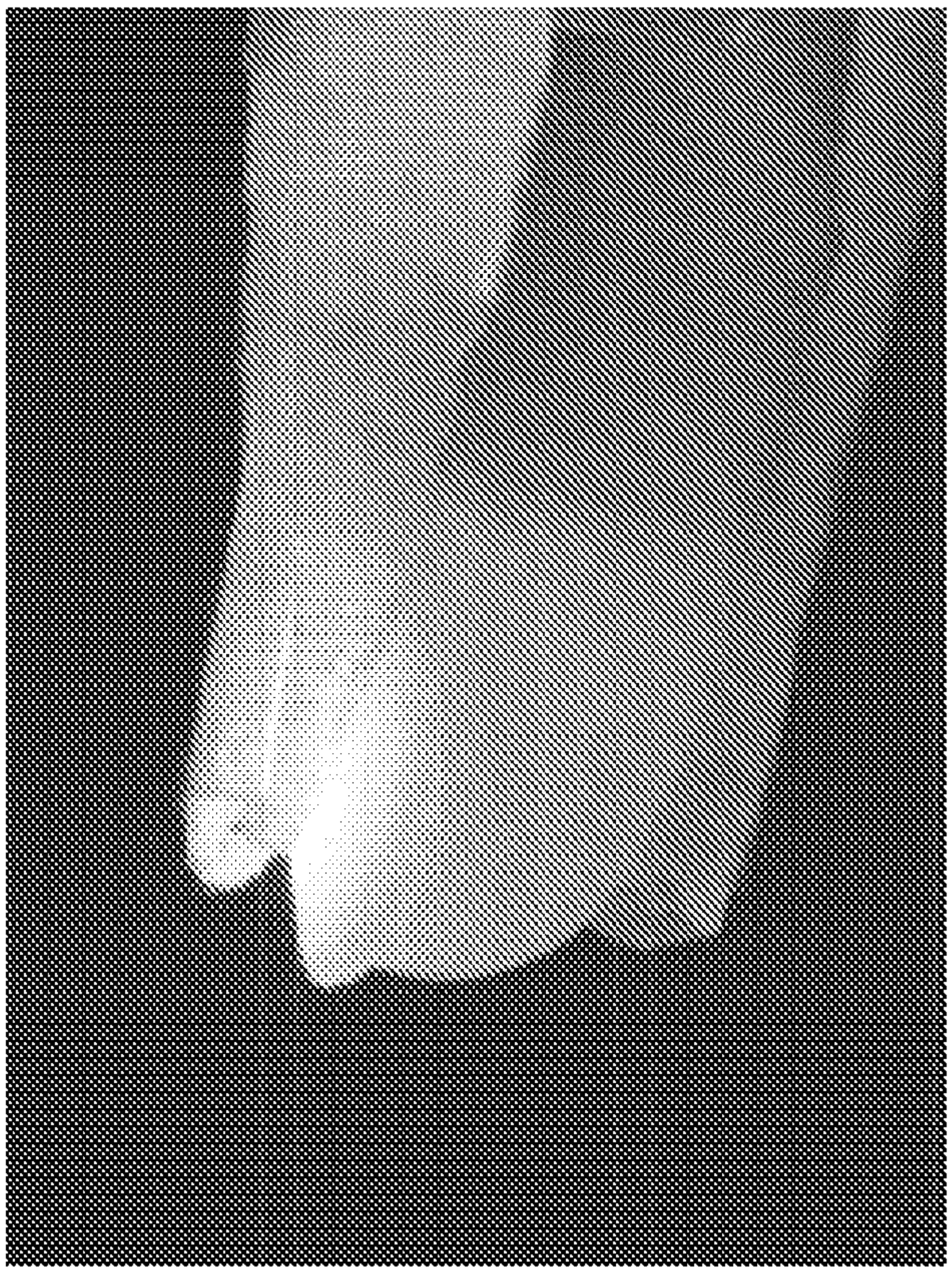


FIG. 4B

STRETCHABLE ELECTRONIC DEVICE AND METHOD OF MAKING THE SAME

CROSS-REFERENCE TO RELATED APPLICATION

[0001] This application is a National Stage Application of International Patent Application No. PCT/US2021/031280 filed May 7, 2021, which claims benefit of priority to U.S. Provisional Patent Application No. 63/022,064 filed on May 8, 2020, the entire disclosure of each of which is hereby incorporated by reference.

STATEMENT OF GOVERNMENT RIGHTS

[0002] This invention was made with United States Government support under Grant No. 1751348, awarded by the National Science Foundation (NSF). The United States Government has certain rights in this invention.

BACKGROUND

[0003] The present invention is directed to flexible and stretchable electronic devices and in particular to methods of making flexible and stretchable electronic devices.

[0004] Wearable monitoring devices are utilized in a growing number of applications. The electronics associated with these monitoring devices must be flexible and stretchable to comply with and conform to the body of the wearer. Typical electronic devices fabricated on a printed circuit board are too rigid for this type of application. Many flexible circuits cannot be stretched, preventing them from conforming to the body of the wearer. It would therefore be desirable to fabricate flexible and stretchable electronic devices that can be utilized on wearable devices.

BRIEF DESCRIPTION OF THE FIGURES

[0005] FIGS. **1***a*-**1***r* are a diagram illustrating the microfabrication steps implemented to fabricate a flexible and stretchable electronic device according to some embodiments;

[0006] FIG. **2***a* is a top view of electrical traces fabricated on a rigid substrate according to some embodiments;

[0007] FIG. **2***b* is a side view of the rigid substrate, detachment layer, sacrificial layer, and electrical trace layer according to some embodiments;

[0008] FIG. **2***c* is a top view of the rigid substrate that includes one or more surface mounted components (SMCs);

[0009] FIG. **2***d* is a side view of the rigid substrate shown in FIG. **2***c* that includes at least one SMC;

[0010] FIG. **2***e* is a perspective view of a flexible and stretchable electronic device;

[0011] FIG. **2***f* is a side view of the flexible and stretchable electronic device according to some embodiments;

[0012] FIG. **2***g* is a perspective view of a transparent, flexible, and stretchable electronic device according to some embodiments;

[0013] FIG. **2***h* is a perspective view of flexible conductive traces in transparent, flexible, and stretchable electronic device according to some embodiments;

[0014] FIG. **3** is a perspective view of a flexible and stretchable electronic device being removed from a rigid substrate according to some embodiments;

[0015] FIG. **4***a* is a perspective view of a flexible and stretchable electronic device being worn on a finger and used in a reflective mode according to some embodiments; and

[0016] FIG. **4***b* is a perspective view of a flexible and stretchable electronic device being worn on a finger and used in a transmissive mode according to some embodiments.

DETAILED DESCRIPTION

[0017] According to some aspects, this disclosure is directed to electronic devices that are stretchable and flexible and to methods of making the same. In some embodiments, a microfabrication method is utilized to fabricate the flexible and stretchable electronic device, hereinafter referred to as the device. As used herein, the term "stretchable" means that the device is capable of being elongated along at least one axis, and preferably multiple axes. Further, as used herein, the term "flexible" means that the device is capable of bending along multiple axes, in contrast with typical flexible printed circuit boards (PCBs) which are capable of flexing along only a single axis. The method utilizes a substrate formed of a rigid material (e.g., silicon, glass, etc.) on which the device is temporarily disposed to fabricate conductive traces and contact pads on which surface mounted electrical components are mounted to be included in the device. In some embodiments, a release layer, e.g., polymethyl methacrylate (PMMA), is deposited on the substrate, followed by a sacrificial layer, e.g., polyimide (PI), which is then cured to provide a rigid carrier on which the remaining microfabrication steps can be carried out. Following fabrication of the electronic components on the temporary rigid substrate, the electronic components are coated with a flexible and stretchable polymeric material that serves as a flexible and stretchable substrate for the device. This is followed by detachment of the electronics and flexible and stretchable substrate from the temporary rigid substrate at the interface between the release layer and the sacrificial layer. The sacrificial layer is subsequently removed from the flexible and stretchable substrate by an etching process and another layer of flexible and stretchable polymer material is provided over the bottom of the device. The end product is an electronic device in a flexible and stretchable substrate that is well adapted for use as a wearable device. The method of fabricating the electronic device, in particular the temporary use of the rigid substrate, allows for the use of high-precision microfabrication techniques capable of providing the desired integration density while providing a flexible and stretchable substrate that is well-suited for applications such as health monitoring of a person wearing the device. The device has the ability to conform to curved surfaces and is therefore useful in a number of applications, including as a wearable device capable of conforming to the body of a medical patient or other user.

[0018] FIGS. **1***a* through **1***r* is a diagram illustrating the microfabrication steps of fabricating a stretchable and flexible electronic device. The method begins at the step shown in FIG. **1***a* with a temporary rigid substrate **100** such as a silicon substrate or glass substrate. In the step shown in FIG. **1***b*, a release layer **102** is deposited on the surface of the temporary rigid substrate **100**. In some embodiments, the release layer **102** is polymethylmethacrylate (PMMA). In some embodiments, the release layer **102** is deposited onto the surface of the temporary rigid substrate **100** by a spin coat process and then heated at a desired temperature for a length of time (e.g., 180° C. for two minutes).

[0019] In the step shown in FIG. **1***c*, a sacrificial layer **104** is deposited on top of the release layer **102**. In some embodiments, the sacrificial layer **104** is polyimide (PI). In some embodiments, the sacrificial layer **104** is deposited onto the surface of the release layer **102** by spin coating and then prebaking at 180° C. and subsequently fully curing in a convection oven at 300° C. under a flow of nitrogen.

[0020] In some embodiments, the adhesion between the release layer **102** and the sacrificial layer **104** is controlled to ensure the bond is sufficient to be maintained during subsequent fabrication steps but can be detached from each other to separate the rigid substrate from the device. Curing the release layer **102** and the sacrificial layer **104** allows the temporary substrate to act as a rigid carrier through the rest of the processing steps.

[0021] In the step shown in FIG. **1***d*, an initial metal layer **106** is deposited on top of the sacrificial layer **104** through a metallization process. In some embodiments, the initial metal layer **106** is deposited using electron beam evaporation. In some embodiments, the initial metal layer **106** is a gold (Au). In some embodiments, the initial metal layer **106** is utilized as a seed layer for subsequent electrodeposition techniques. In this embodiment, the seed layer may be relatively thin (e.g., approximately 400 nm thick). In some embodiments, plasma activation of the initial metal layer **106** is utilized to increase the surface adhesion of the initial metal layer **106** to the sacrificial layer **104**.

[0022] In the step shown in FIG. **1***e*, photolithography techniques are utilized to pattern the initial metal layer **106**. In some embodiments, this includes deposition of a mask layer **108** on the initial metal layer **106**.

[0023] In the step shown in FIG. **1***f*, a thicker metal layer **110** is electrodeposited using the initial metal layer **106** as a seed layer.

[0024] In the step shown in FIG. **1***g*, the mask layer **108** is removed from the initial metal layer **106**.

[0025] In the step shown in FIG. **1***h*, the initial metal layer **106** is removed (e.g., chemically etched) to expose metal contacts **112***a*, **112***b* and traces (not visible) in the desired pattern. In some embodiments, rather than a single layer of electrical traces and metal contacts **112***a*, **112***b*, the process may be repeated to fabricate a plurality of layers of electrical traces and/or contacts, which conductive layer (including electrical traces and/or contacts) separated by a flexible and stretchable insulative layer. In some embodiments, conductive vias are fabricated in the insulative layer located between the one or more conductive layers to provide a multi-layer flexible and stretchable circuit. In some embodiments the flexible and stretchable insulative layer is the same as the flexible and stretchable substrate described in more detail with respect the steps shown in FIGS. **1***m* through **1***q* and the deposition process may be essentially the same. In some embodiments, the flexible and stretchable insulative layer may also be patterned according to the desired via interconnects. In other embodiments, other material may be utilized between the layers of electrical traces and/or contacts but the material utilized should be both non-conductive (insulative) as well as flexible and stretchable. In some embodiments, one of the plurality of layers may include a conductive grounding layer. In some embodiments, the conductive grounding layer is fabricated utilizing a conductive polymer to provide the desired conductivity in combination with the desired flexibility and stretchability. At this stage in the process, the substrate is ready for mounting of surface mounted electrical components (SMCs) onto the metal contacts **112***a*, **112***b*. Depending on the application, a plurality of different types of SMCs may be utilized, including optical devices, electro-optical devices, electro-mechanical devices, etc. For example, in one application the SMCs include one or more active optical devices (e.g., light emitting diodes, lasers, etc.) and one or more optical sensors for measuring backscattered light.

[0026] In some embodiments, mounting of SMCs utilizes a lithography and dip coating process to deposit the solder at the desired location on the metal contacts **112***a*, **112***b*. In some embodiments, as shown in FIG. **1***i*, lithography techniques are utilized to deposit a mask layer **114**. As shown in FIG. **1***i*, the mask layer **114** exposes a small portion of the metal contacts **112***a*, **112***b*.

[0027] In the step shown in FIG. **1***j*, the substrate is dip coated in a molten solder bath, which results in solder layers **116** being deposited onto exposed portions of the metal contacts **112***a*, **112***b*.

[0028] In the step shown in FIG. **1***k*, the mask layer **114** is removed by a stripping process, leaving the solder layer **116** positioned on the metal contacts **112***a*, **112***b* as desired.

[0029] In the step shown in FIG. **1***l*, a surface mounted device (SMC) **118** is placed onto the metal contacts **112***a*, **112***b* and the solder is heated causing it to reflow and allow self-assembly of the SMC **118** on the metal contacts **112***a*, **112***b*. At this point in the microfabrication process, the device can be electrically and mechanically tested. In some embodiments, these steps may utilize automated microfabrication techniques. For example, pick and place machines may be utilized to place the SMCs **118** on the desired contact pads. In addition, optical registration techniques may be utilized to verify placement of metal contacts **112***a*, **112***b* and/or SMCs **118**.

[0030] In the steps shown in FIGS. **1***m* through **1***q* and in FIG. **3**, the temporary rigid substrate is removed and replaced with a soft, compliant substrate **120**. In some embodiments, the soft, compliant substrate **120** is clear, i.e., transparent, to allow optical signals to be transmitted to and from the SMCs **118**. In some embodiments, in the step shown in FIG. **1***m*, a polymer resin is applied to the substrate in an over-molding step. In some embodiments the polymer resin is a transparent urethane rubber material, e.g., CLEAR FLEX™ manufactured by Smooth-On Inc. of Macungie, Pa., that is comprised of two component polymers mixed together in a predetermined ratio (e.g., 1A:2B). As shown in FIG. **1***m*, over molding of the polymer resin results in the SMCs **118** as well as the other sacrificial layer **104** being covered by the polymer resin. As described above, in some embodiments the polymer resin is transparent. In some embodiments, the assembled components are treated with ozone for a length of time to increase the bonding strength between the components and the compliant substrate **120**. In some embodiments, the compliant substrate **120** is cured. In some embodiments, the polymer resin is flexible and stretchable. At this stage, the temporary rigid substrate—which includes the temporary rigid substrate **100**, release layer **102** and sacrificial layer **104**—is still affixed to the electronic components on a bottom side. The compliant substrate **120** is located opposite the temporary rigid substrate **100**, affixed to the top side (as discussed in more detail below in the next step, the substrate is flipped wherein the top side becomes the bottom side).

[0031] In the step shown in FIG. **1***n*, the temporary rigid substrate **100** is separated from the electrical device (e.g., SMCs **118** and conductive traces) at the interface between the release layer **102** and the sacrificial layer **104**, wherein the sacrificial layer **104** remains affixed to the compliant substrate **120**. The process of separating the compliant substrate **120** from the temporary rigid substrate **100** is dry i.e., no solvent is necessary to make the separation. This separation relies on a differential interfacial adhesion between PMMA and PI materials. A first adhesion force between the PMMA material forming the release layer **102** and the silicon material forming the temporary rigid substrate **100** is stronger than a second adhesion force of the PI material forming the sacrificial layer **104** to the PMMA material forming the release layer **102**. When a removal force greater than the second adhesion force is applied to the compliant substrate **120** it detaches from the temporary rigid substrate **100** at the PMMA-PI interface. A single transfer step for the entire device/circuit is also scalable.

[0032] In the step shown in FIG. **1***o*, the sacrificial layer **104** is removed from by a plasma etching process. As shown at in FIG. **1***o*, the compliant substrate **120** is flipped upside down, wherein the plasma etching process removes the sacrificial layer **104** from the compliant substrate **120**. Following the step shown in FIG. **1***o*, electrical contacts and traces are exposed on the (now) top side of the compliant substrate **120**.

[0033] In the step shown in FIG. **1***p*, electrical contacts are established as a required and in the step shown in FIG. **1***q*, a polymer layer **122** is deposited on top of the device to fully encapsulate the device. The final device is shown in FIG. **1***r*.

[0034] In this way, the method described above utilizes a rigid substrate to pattern and place electrical components in the density required utilizing microfabrication techniques. Following fabrication of the device the temporary rigid substrate is removed and the device is encapsulated in a stretchable silicone substrate.

[0035] Referring now to FIGS. **2***a*-**2***f*, the flexible and stretchable electronic device is illustrated at several different stages of manufacture as well as in operation. FIG. **2***a* is a top view of electrical traces fabricated on a temporary rigid substrate according to some embodiments. In this view, a temporary rigid substrate **200** supports a plurality of conductive traces **202** as well as a plurality of electrical contacts **204**. As discussed above, utilization of a rigid substrate allows traditional microfabrication techniques to be utilized, allowing for density of conductive traces **202** and density of electrical contacts **204** not possible without microfabrication techniques. In the embodiment shown in FIG. **2***a*, conductive traces **202** have a geometry designed to accommodate stretching and/or bending of the device.

[0036] FIG. **2***b* is a side view of the device shown in FIG. **2***a*, in which a temporary rigid substrate **200** includes a rigid silicon substrate **205**, a release layer **208** (e.g., PMMA) and a sacrificial layer **210** (e.g., PI). As described above, the release layer **208** and the sacrificial layer **210** are cured to ensure that temporary rigid substrate **200** is sufficiently rigid to fabricate electrical traces and mount surface mounted components (SMCs) as shown in FIG. **2***c*. In this example, conductive traces **202** and electrical contacts **204** have been deposited and fabricated on top of the temporary rigid substrate **200**.

[0037] FIG. **2***c* is a top view that illustrates a plurality of surface mounted components (SMCs) **234** that are mounted to the temporary rigid substrate **200** according to some embodiments. In this view, the temporary rigid substrate **200** provides support during the mounting and soldering of the plurality of SMCs **234** onto the electrical contacts **204** shown in FIGS. **2***a* and **2***b*. In some embodiments, placement of the plurality of SMCs **234** may take advantage of pick-and-place commonly utilized with microfabrication techniques.

[0038] FIG. **2***d* is a side view of the device shown in FIG. **2***c*, in which SMCs **234** are mounted on the electrical contacts **204**. At this time, the temporary rigid substrate **200** provides the rigidity necessary to mount the SMCs **234** onto the electrical contacts. In some embodiments, pick and place machines are utilized to mount the plurality of SMCs **234** onto the desired electrical contacts **204**. A benefit of utilizing a rigid substrate (i.e., the temporary rigid substrate **200**) during this process is that it allows for standard microfabrication techniques—such as pick and place machines—to be utilized to fabricate the electronic device. As described above with respect to FIGS. **1***a*-**1***r*, following placement of the surface mounted components on the electrical contacts **204**, the temporary rigid substrate **200** is removed and the remaining components are encased in a flexible and stretchable polymer layer as shown in FIGS. **2***e* and **2***f*.

[0039] With respect to FIG. **2***e*, an embodiment is shown in which the flexible and stretchable electronic device **215** includes a plurality of surface mounted optical devices. In particular, in the embodiment shown in FIG. **2***e*, the device includes an infrared (IR) LED **220**, a red-green-blue (RGB) LED **222**, an IR phototransistor **224**, and a visible light phototransistor **226**. Each of these components represents a type of surface mounted device (SMC) mounted onto the electrical contacts **204** shown in FIG. **2***a*. In addition, the embodiment shown in FIG. **2***e* illustrates a clear flexible and stretchable polymer substrate **228** surrounding the conductive traces **202** and SMR devices, including IR LED **220**, RGB LED **222**, IR phototransistor **224**, and visible light phototransistor **226**. As illustrated in FIG. **2***g*, the geometry of the conductive traces **202** (e.g., undulating, meandering, sawtooth, and/or serpentine geometry) allows the conductive traces **202** to handle bending and/or stretching. Likewise, the flexible and stretchable polymer substrate **228** is capable of handling bending and/or stretching. In addition, in applications in which one or more of the SMCs are optical devices requiring to transmit and/or receive transmitted light, it is important that the flexible and stretchable polymer substrate **228** be transparent or nearly transparent to allow the transmission of light to and from the optical devices.

[0040] FIG. **2***f* is a side view of the device shown in FIG. **2***e*. In the embodiment shown in FIG. **2***f*, the entire device is encapsulated in the flexible and stretchable polymer substrate **228**. Encased within the flexible and stretchable polymer substrate **228** is a pair of electrical contacts **230***a*, **230***b*, a pair of solder joints **232***a*, **232***b*, and SMCs **234** (e.g., IR LED **220**, RGB LED **222**, IR phototransistor **224**, or visible light phototransistor **226**). The geometry of the conductive traces **202** ensures that the stretchability and flexibility of the device does not prevent electrical conductivity between the electrical contacts **230***a*, **230***b*, solder joints **232***a*, **232***b*, and the SMCs **234**.

[0041] FIG. **2***g* is a perspective view illustrating the transparent and stretchable electrical device fabricated as shown in FIGS. **2***a*-**2***f* in operation. In particular, the embodiment shown in FIG. **2***g* illustrates the use of optoelectronic devices, which can be utilized in a plurality of patient and health monitoring applications.

[0042] Although the embodiment shown in FIGS. **2***a*-**2***e* utilizes a plurality of optoelectronic devices, in other embodiments various other configurations of optoelectronic devices and/or other electrical devices may be microfabricated on the flexible and stretchable substrate. For those applications that do not require transmission of light, the stretchable substrate is not required to be transparent.

[0043] While the invention has been described with reference to an exemplary embodiment(s), it will be understood by those skilled in the art that various changes may be made, and equivalents may be substituted for elements thereof without departing from the scope of the invention. In addition, many modifications may be made to adapt a particular situation or material to the teachings of the invention without departing from the essential scope thereof. Therefore, it is intended that the invention is not limited to the disclosed embodiment(s), but that the invention will include all embodiments falling within the scope of the appended claims.

1. A method of manufacturing a stretchable electronic device, comprising:
- depositing a release layer on a temporary rigid substrate;
- depositing a sacrificial layer on the release layer;
- fabricating a plurality of conductive traces and electrical contacts on top of the sacrificial layer;
- mounting one or more surface mount components to the electrical contacts;
- depositing a first stretchable polymer layer on top of the conductive traces and surface mount components to form a stretchable substrate;
- separating the temporary rigid substrate and release layer from the sacrificial layer and the stretchable substrate at an interface between the release layer and the sacrificial layer;
- removing the sacrificial layer from the stretchable substrate; and
- depositing a second stretchable polymer layer on a surface of the stretchable substrate exposed by removing the sacrificial layer.

2. The method of claim **1**, wherein the first and second stretchable polymer layers are flexible.

3. The method of claim **1**, wherein the first and second stretchable polymer layers are formed of a urethane rubber material.

4. The method of claim **1**, wherein the release layer is formed of polymethyl methacrylate.

5. The method of claim **1**, wherein the sacrificial layer is formed of polyimide.

6. The method of claim **1**, wherein the sacrificial layer is removed from the first stretchable polymer layer by a plasma etching process.

7. The method of claim **1**, wherein the temporary rigid substrate is formed of a silicon-based material.

8. The method of claim **1**, wherein the first stretchable polymer layer is transparent.

9. The method of claim **8**, wherein the one or more surface mount components are optoelectronic devices.

10. The method of claim **1**, wherein the plurality of conductive traces is stretchable and flexible.

11. The method of claim **10**, wherein the plurality of conductive traces has an undulating, meandering, sawtooth, or serpentine geometry.

12. A stretchable electronic device comprising:
- a plurality of conductive traces;
- one or more electrical contacts in electrical communication with the plurality of conductive traces;
- one or more surface mounted components mounted to the one or more electrical contacts; and
- a stretchable substrate surrounding the plurality of conductive traces and the one or more surface mounted components.

13. The stretchable electronic device of claim **12**, wherein the stretchable substrate is flexible.

14. The stretchable electronic device of claim **12**, wherein the plurality of conductive traces is stretchable.

15. The stretchable electronic device of claim **12**, wherein the plurality of conductive traces is flexible.

16. The stretchable electronic device of claim **15**, wherein the plurality of conductive traces has an undulating, meandering, sawtooth, or serpentine geometry.

17. The stretchable electronic device of claim **12**, wherein the stretchable substrate is transparent.

18. The stretchable electronic device of claim **17**, wherein the one or more surface mounted components are optoelectronic devices.

19. The stretchable electronic device of claim **18**, wherein the optoelectronic devices include a photo generation device and a photo detector device.

20. A stretchable electronic assembly, comprising:
- two stretchable electronic devices according to claim **12**, wherein the two stretchable electronic devices are stacked on one another and wherein conductive traces in the two stretchable electronic devices are connected by one or more conductive vias extending between the two stretchable electronic devices.

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